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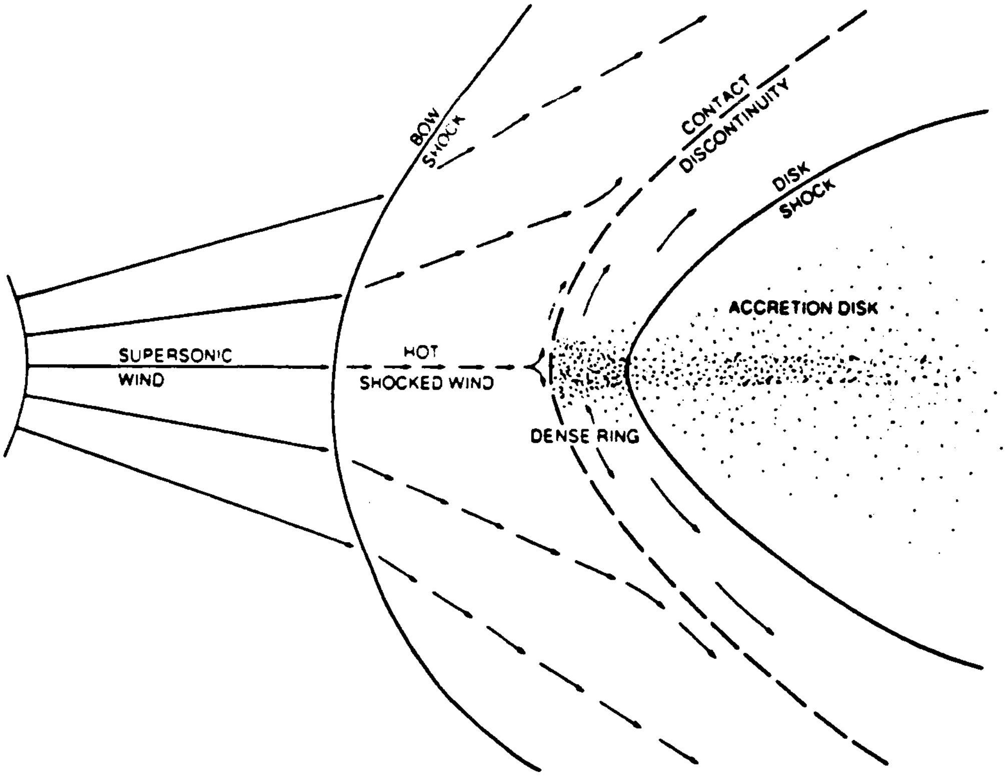
WORKSHOP ON
THE ORIGINS OF SOLAR SYSTEMS



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WORKSHOP ON THE ORIGINS OF SOLAR SYSTEMS

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Cover: Schematic cross section of the shock front between a supersonic protostellar wind and an accretion disk during one of the many early-pre-main-sequence protostellar eruptions. The geometry of the interaction front is governed by the distribution of gas and dust around the protostar. The wind pushes back surrounding gas and dust until momentum balance is attained across the contact discontinuity. A bow shock propagates back toward the protostar, decelerating the highly supersonic wind and heating it to very high temperature. A series of disk shocks propagates into the accretion disk at 1–2 km s^{-1} (in the rest frame of the inwardly moving disk material), warming the disk ahead of the advancing interaction front. The rate at which the interaction front advances into the accretion disk is governed by the rate at which material in the dense ring is heated and lost through thermal motion perpendicular to the disk plane. From G. R. Huss, 1987, Ph.D. thesis, University of Minnesota.

EXECUTIVE SUMMARY

ORIGINS OF SOLAR SYSTEMS: A PROPOSED INTERDISCIPLINARY INITIATIVE

The development of NASA's Space Science program starting nearly three decades ago marked the transition of the quest to understand the origin of the solar system, from individual quixotic theorizing, based on totally inadequate data, to a systematic, multidisciplinary research program. Astrophysicists have modeled and observed in ever-increasing detail regions of modern star formation. Planetary scientists and meteoriticists have exacted a wealth of new information on conditions in the early solar nebula. Exobiologists have extended the study of the chemical and biological evolution of life back beyond the beginnings of life on Earth to look at the larger question of the prevalence of life in the universe. Each of these once distinct scientific disciplines has begun to examine problems that had previously been considered to be outside the boundaries of its expertise. Researchers in each of these disciplines are often unaware of the considerable body of literature from other fields that is directly applicable to their studies. The richness of the results that have been obtained by NASA's Solar System Exploration, Astrophysics, and Life Science programs can be utilized very effectively to study the origins of solar systems if an umbrella, interdisciplinary program is created that fosters contacts between the various disciplines. Within this program, mutually supportive roles will be played by observation, experiment, theory, and computation in the pursuit of a detailed understanding of the processes by which planetary systems form. A scientific steering committee will ensure that cross-disciplinary research efforts are given high priority and visibility through a focused series of workshops, conferences, and symposia on relevant aspects of the origins of solar systems. The minimum incremental cost for a viable umbrella research program, which will add considerably to a wide variety of scientific and flight programs currently supported within OSSA, is estimated to be $6M per year. It is suggested that this program receive high priority in the 1990 NASA budget request.

The time is right for a major, coordinated research effort on the problem of the "Origins of Solar Systems." This program should involve elements of research presently part of three OSSA divisions: Solar System Exploration, Astrophysics, and Life Sciences. For the first time in humanity's long speculations on this topic, astronomers have obtained strong hints of the existence of planetary systems other than our own. The IRAS satellite has discovered dust rings around mature stars such as Vega and Beta Pictoris, there is infrared evidence for a brown-dwarf companion to Giclas 29-38, and observations at millimeter, infrared, and optical wavelengths suggest that nebular disks surround many newly formed solar-type stars. Thus, we stand on the threshold of having concrete empirical evidence to explain the origin of our solar system, which must have involved the processes of grain agglomeration, planetary accumulation, and disk dispersal. Theory and observations of star formation have reached a stage where the development of disks and/or binary star systems is viewed as a natural byproduct of the gravitational collapse of a rotating molecular-cloud core.

In 1986, mankind had its first close-up view of Halley's comet, an active system with a startlingly black nucleus, from which *in situ* information about a small primitive solar-system body was gathered. The unexpected wealth of carbon-hydrogen-oxygen-nitrogen particles provided new insights into the production of biogenic compounds early in solar-system history. Early observations from the Giotto mission revealed CH_4/CO ratios that are much greater than the present observational limits for this ratio in the interstellar medium or the values predicted for the solar nebula. These observations thus reinforce the necessity for coupled studies of nebular chemistry and dynamics for understanding the composition of primitive volatile-rich solar-system bodies.

In parallel with the astronomical observations, presolar isotopic anomalies have been discovered in meteorites. Some of these anomalies may be associated with specific stellar environments such as supernovae and red giants. The carriers of these anomalies provide unique information on circumstellar-grain formation and the population of interstellar grains. In addition, analysis of the decay products of extinct radionuclides is supplying an increasingly detailed picture of the time scale for early solar-system processes. The recognition of meteorites plausibly derived from Mars yields valuable clues to the bulk isotopic and chemical composition of a planetary body 0.5 A.U. from Earth. Laboratory studies of elemental partitioning between metal and silicate in terrestrial and meteoritic samples permit evaluation of accretional processes, and suggest that Earth may have accreted heterogeneously, while Mars may have accreted homogeneously. Numerical studies of planetary accumulation have led to a picture that could account for the gross chemical and dynamic features of the terrestrial planets.

The study of the origin of life is part of the continuum of investigations into the origin and evolution of the biogenic elements and compounds from their nucleosynthetic origin, through transformation within interstellar environments, incorporation into the solar nebula, and eventual delivery to the early Earth. These studies have increased the conviction that life, as we know it, arose as a natural consequence of the formation of the solar system. The evolution of life has both profoundly influenced, and has itself been constrained by, Earth and its astrophysical environment; life is indeed a planetary phenomenon. It is now time to expand these studies to consider whether this evolutionary sequence may have been repeated in other solar systems.

Several important phases of solar system formation are not amenable to astronomical observation or laboratory experimentation, so that numerical simulations may be our only means of learning more about these phases for the foreseeable future. Examples include much of the collapse phase leading to the presolar nebula, the consequences of giant impacts on the subsequent evolution of a planet, and gravitational instabilities in the disk of gas and dust composing the nebula. The extraordinary development of supercomputers in the last few years has meant that these numerical simulations, often three-dimensional in nature, can now be performed with increasing realism.

In recognition of the timeliness and importance of this subject, the Solar System Exploration Division convened two workshops on the origins of solar systems that were held in December of 1986 and 1987. The major goal of these workshops was to explore the potential for complementary, interdisciplinary efforts to solve several key scientific questions not adequately addressed at the present time by any single research community. A secondary goal was to assess the need for and potential rewards from a focused research effort on the origins of solar systems. Such an effort would unite various aspects of the following areas: interstellar chemistry, theoretical and observational studies of protostars, solar nebula models, meteorites and primitive bodies, planetary accumulation and evolution, and the origin of life. Four interdisciplinary working groups were established in an effort to bridge the traditional boundaries between these fields. Some of the key scientific questions identified by these groups are summarized below. Detailed recommendations are contained in the full reports of the individual working groups and in the series of invited lectures on various aspects of this problem that were delivered during the 1986 workshop. A plan for a comprehensive research initiative focused on this interdisciplinary problem was developed during the second workshop by representatives of the astrophysics, meteoritics, exobiology, and planetary sciences communities. A brief outline of this plan will be given after discussion of the research efforts recommended by the working groups.

I. Interstellar Chemistry and Primitive Bodies

Four areas, described below, were identified in which specific observational, analytical, or laboratory studies are necessary in order to understand the degree of mixing and processing of material in circumstellar, interstellar, and nebular environments.

Determination of the smallest-scale chemical and isotopic inhomogeneities characteristic of molecular clouds that are ancestral to planetary systems could be made by studying the gaseous and condensed species using groundbased millimeter arrays and IR cameras, and airborne and eventually spacebased IR telescopes. Determination of the distribution of isotopic and chemical anomalies in a variety of primitive bodies could be used to deduce spatial scales of variation within the early solar nebula. Further investigation of the primitive components in meteorites, interplanetary dust particles, and comets could provide evidence to determine the minimum number of specific nucleosynthetic sources that have contributed material to the solar system. Finally, laboratory and theoretical studies of astrophysical processes appropriate to circumstellar, interstellar, and nebular environments are needed to determine: rates of nonequilibrium gas-phase and gas-grain reactions, characteristic isotopic fractionation effects for these processes, and the morphological and structural properties of primitive condensates and aggregates.

II. Astronomical Measurements and Nebula Models

Three specific problem areas in our current concept of the manner in which planetary systems form and in which collaborative efforts between observational astronomers and nebula modelers might yield exciting advances are the following: the initial collapse of a protostellar cloud to form a nebula, especially the properties and evolution of secondary concentrations of gas and dust ranging in size from Jovian to stellar; the growth of solid objects into planetesimal-sized bodies; and the interaction of the evolving star with the surrounding nebula.

A few examples of collaborative projects in these areas that would help to unite the efforts of observers and modelers are briefly described below. Observations of star-forming regions at high spatial and spectral resolution should be made so that velocity, density, temperature, and compositional distributions can be determined for evolving protostellar nebulae. High-sensitivity visible and infrared searches for the largest members of a possible inner Oort cloud of comets in our solar system between about 50 and 100 A.U. should be undertaken in order to improve the determination of the radial distribution of planetesimal material. Both of these observational projects would provide valuable constraints on models of the solar nebula. Theoretical studies of the interaction of a strong stellar wind with a protoplanetary disk can be carried out in sufficient detail so that the models can be compared with high-resolution astronomical observations. From such studies we may be able to understand, for example, the processes responsible for the removal of nebular gas, or to make predictions about the structure expected for particular protostellar nebulae that could then be verified by observational studies.

III. Solar Nebula Models and Meteorites

Several key areas of investigation can help to bridge the gap between large-scale astrophysical models of the solar nebula and the detailed but limited data available from meteorites. Specific examples of studies recommended by this working group are described below.

Hydrodynamic simulations of convection and/or density waves in the disk are needed to quantify the extent of mixing between different nebular regions. Analytical and numerical studies of particle-gas dynamics must be carried out in order to model the aerodynamic sorting and transport of particles during planetesimal formation. Quantitative inventories of the diverse components of meteorites should be compiled in order to constrain models of mixing and accretion in the nebula. Searches for meteoritic evidence of compositionally anomalous regions in the nebula, and modeling of the formation of such regions by settling, evaporation, and condensation in the disk are necessary if we are to extract nebular constraints from the meteoritic data.

Searches for evidence in meteoritic grains of a T-Tauri stage of the early sun could serve to constrain the extent and effect of this stage of stellar evolution on material in the nebula. Similarly, laboratory experiments and computer modeling to determine the physical and chemical properties of grain aggregates could be used to provide more realistic estimates for the opacity of the nebula or the mechanics of grain-grain collisions. Application of radiochronological data for meteorites could be used to establish a time scale for processes that occurred in the nebula. Finally, studies of the formation of asteroids, their collisional evolution, and the delivery of asteroidal material to Earth and the other terrestrial planets are essential if we are to understand the meteoritic evidence in sufficient detail to constrain models of the solar nebula.

IV. Planetary Accumulation and Evolution

The broad problems of the accumulation of planets from planetesimals, the addition of planetary volatiles (including the massive mantles of Jupiter and Saturn), and the subsequent early evolution of the planets can be addressed through three complementary approaches. These are: numerical and theoretical studies of planetary formation, experimental studies of the physical and chemical processes relevant to planetary growth, and geochemical studies of meteorites and other appropriate planetary materials.

Within this broad framework many specific problems can be identified that may be pursued by independent investigators using one or more of these complementary approaches. For example, one such group of investigations of great importance are those directed toward understanding the physical and chemical mechanisms by which nebular dust particles aggregate to form small planetesimals. Another concerns the manner in which these planetesimals combine to form planetary bodies. In this regard, the formation of Jupiter's core and hydrogen-helium mantle is of special interest, inasmuch as phenomena initiated by an early-formed Jupiter could to a large extent control the subsequent evolution of the rest of the planetary system.

The asteroids are especially sensitive to events accompanying the formation of Jupiter. A better understanding of both the dynamical events to be expected in the asteroid belt and the related chemical, mineralogical, and isotopic effects observable in asteroidal meteorites is required in order to reveal the history of these events.

As results of the kind illustrated by these examples become available, these often specialized individual studies, oriented toward long-range goals, will combine to provide "building blocks" for the continuing grander effort of synthesizing the history of our solar system.

RECOMMENDED PROGRAM PLAN

Participants at the workshop felt that a viable program of research into the origins of solar systems would require a commitment of approximately \$6M per year for a period of at least six years. This level of funding would support between 50 and 100 principal investigators, provide between \$1 and \$2M per year for the purchase or upgrade of research equipment, support several focused workshops each year, and provide the necessary funds to cover the administrative aspects of the program. It was recommended that individual principal investigators be funded for a period of three years and that the entire program undergo a review after five years. Due to the interdisciplinary nature of this research effort, it was felt that the responsibility for the administration of the program should reside in the office of the Assistant Associate Administrator for Science within OSSA, who would be assisted by a steering committee and would delegate much of the responsibility for peer review and the day-to-day management of the effort to appropriate Discipline Scientists within the OSSA Divisions.

Contents

Introduction

In December, 1986, the first of two workshops was held on the Origins of Solar Systems. This workshop brought together astrophysicists, meteoriticists, planetary scientists, and exobiologists, among others, to discuss the possibility that researchers interested in the formation of stellar and planetary systems might benefit from an exchange of information and the fresh perspective of another field. The first day of the meeting was devoted to a series of invited tutorials that not only summarized the "conventional wisdom" in a particular field but also discussed unsolved problems and areas where concentrated research efforts might lead to significant advancement. These invited presentations are contained in Section I, which closes with the transcript of Dr. George Wetherill's invited summary presentation, given on the evening of the first day.

On the second day of the meeting, the participants broke into four working groups. These groups discussed the relationships between interstellar chemistry and the meteorite record, between nebula models and astronomical observations, between nebula models and meteorites, and between the nebula and the processes of planetary accumulation and evolution. Reports from these working groups were discussed in plenary sessions during the morning and afternoon. On the last morning of the meeting, a general discussion of the utility of a focused interdisciplinary research effort on the origins of solar systems made clear that such an initiative could pay significant scientific dividends if it were properly funded and administered.

The goals of the second workshop, held in December, 1987, were to refine the scientific rationale for a focused interdisciplinary research initiative on the origins of solar systems and to recommend a management plan that would ensure maximum cross-discipline interaction. The reports of the working groups generated after the first workshop were discussed and refined on the first day and evening of the second workshop. These documents are included in Section II of this report. A summary of these reports was also begun that evening that eventually became the Executive Summary.

During the second and third day of the workshop, the participants discussed a large number of management options and schemes currently employed within NASA and OSSA. As agreement was reached on various issues, the Program Plan was drafted by small subsets of the participants and these draft documents were usually the subjects of considerable discussion in plenary session. The management plan finally recommended by the participants can be found in Section III of this report. It is this plan that is the basis of our proposal for the creation of a $6M per year research effort to study the origins of the solar systems beginning in fiscal year 1990.

Section I: Invited Presentations

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INVITED TALK

STAR FORMATION AND MOLECULAR CLOUDS

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INTRODUCTION

There are about as many theories on the formation of the solar system as there are theorists working in the field. This proliferation of star formation theories is due partly to the complexity and wide range of the processes involved and partly to a paucity of observed facts. Thus, while many processes have to be seriously considered, only few constraints are available to discriminate one theory from another. This problem is even further compounded by the question of universality. It is often assumed that planet formation is a frequently-occurring by-product of star formation. The recent detections of particle disks around Vega and β-Pic give strong support for this notion. However, presently there is little known about the general properties of planetary systems, and the applicability of information contained within the solar system to the star formation process and vice versa should be considered an open question. Because the observed facts that have to be explained by the ultimate star formation theory are not universally agreed upon, it is very difficult to objectively review the current status of theories of star formation and any review has to be personal to some extent. An impression on the diversity of the field can be obtained by comparing recent reviews, such as those contained in *Black and Matthews* (1985) and *Lucas et al.* (1985). Other useful reviews on star formation have recently been presented by *Boss* (1987) and *Shu et al.* (1987).

STAR FORMATION

Several different stages can be discerned within the star formation process. Star formation can be considered to start when a molecular cloud fragments into many clumps. Each of these clumps may fragment further or may collapse to form a centrally condensed object with a planetary disk around it. The actual collapse phase itself can be separated into two stages. Initially, when the collapsing fragment is optically thin the collapse occurs isothermally. However, due to the contraction the optical depth through the fragment increases and the latter phase of the collapse will occur adiabatically. As a result the temperature in the interior will rise and ultimately nuclear processes can start in the interior, replacing the gravitational energy as the dominant energy source. Finally, while the inflow may still be feeding the accretion disk, a wind from the star has reversed the inflow on the central object. This wind may blow away all of the surrounding clump material, revealing the newly formed star. Figure 1 (adapted from *Shu et al.*, 1987) shows a schematic overview of the star formation process.

Many different physical processes are likely to play an important role in star formation, including self-gravity, magnetic fields, rotation, winds, and radiation transport. This section reviews our current knowledge on some of these.

Properties of Molecular Clouds

The properties of molecular clouds vary depending on the size scale under consideration. Large clouds, so-called Giant Molecular Clouds (GMCs), have masses, sizes, densities, and temperatures in the range of 10^5–10^6 $M_\odot$, 50 pc, 100 cm^{-3}, and 10 K, respectively (*Scoville and Sanders*, 1987). Massive stars ($M_* > 20$ $M_\odot$) seem to be formed only in these types of clouds. The high flux of (ionizing) radiation locally sets the molecular cloud aglowing and produces optically visible HII regions and reflection nebulae surrounding these young stars. The appearance on the sky of such a cloud, and the OB associations formed in it, often leave the impression of sequential star formation. That is, one generation of stars has triggered the formation of the next generation (*Elmegreen and Lada*, 1977). The Orion molecular cloud is a well-known example of a GMC.

Smaller clouds with masses and radii in the range of 10^3–10^4 $M_\odot$ and 2–5 pc, respectively, lack such massive stars and their associated nebulosities. They appear therefore on the sky as dark, obscuring patches of material. These dark clouds form exclusively low mass stars ($M_* \approx$

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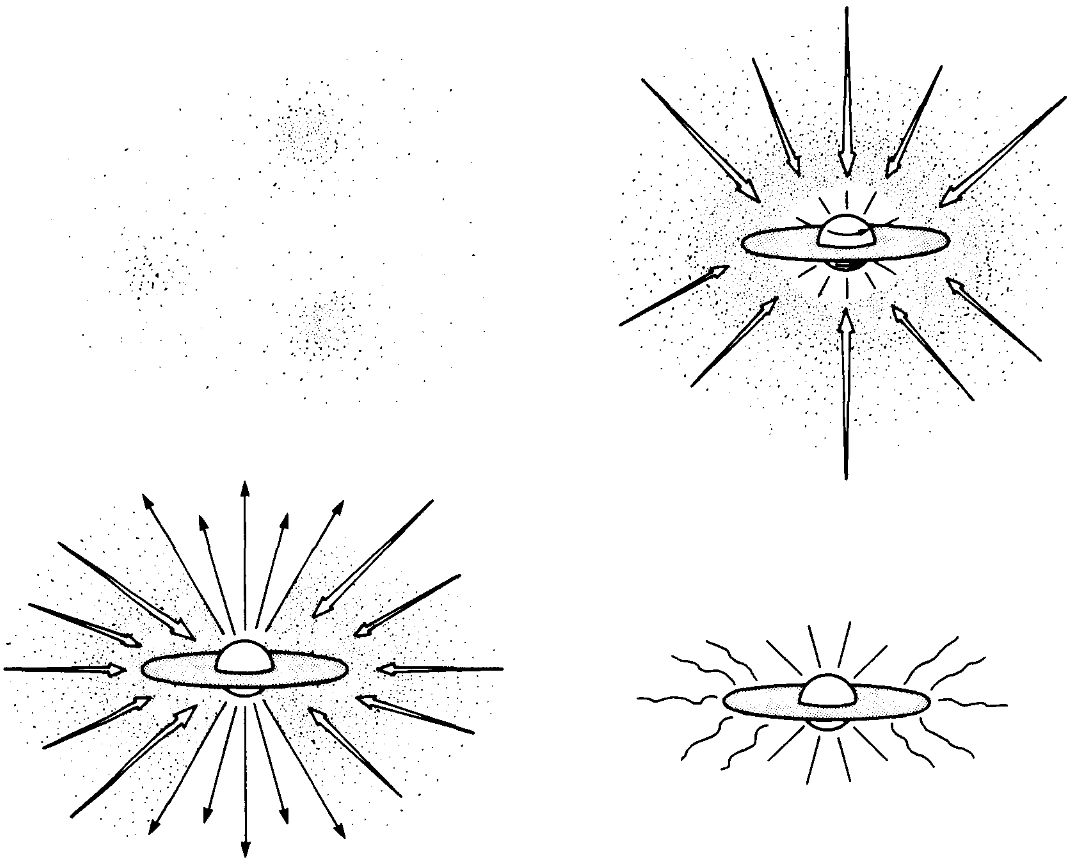

Fig. 1. A schematic overview of the star formation process (taken from *Shu et al.*, 1987). Star formation starts with the formation of dense clumps in molecular clouds (upper left). These rotating clumps undergo gravitational contraction. Conservation of angular momentum leads to the formation of a central object surrounded by an accretion disk (upper right). A powerful wind originates from the protostellar surface or the near surroundings of the protostar and reverses the flow of the infalling material (lower left). Eventually, the protostar and its surrounding planetary accretion disk will become visible (lower right).

1 $M_\odot$). The Taurus cloud is a well-known example of a dark cloud. These dark clouds contain many small (≈0.1 pc), dense (≈3×10^4 cm^{-3}) cores. The detection of IR objects detected by IRAS as well as optical visible T-Tauri stars suggests that these cores are the site of low mass star formation (*Myers*, 1987).

This division into two distinct classes of clouds is quite arbitrary and reflects to some extent the history of this subject. Actually, there seems to be a continuous sequence of cloud properties from the GMCs to clouds with masses in the range of tenths of solar masses. Moreover, the difference in the product of star formation (e.g., O and B stars versus G stars) is also less distinctive than might be discerned at first glance from this discussion. Although massive stars form exclusively in GMCs, there are many GMCs without evidence for massive star formation (*Scoville and Sanders*, 1987). Furthermore, lower mass stars ($M_* \approx$ 1 $M_\odot$) also form in GMCs. However, in contrast to the O and B stars, they seem to occur throughout the whole cloud, independent of a triggering mechanism. Generally, it is therefore agreed that there are two independent star formation processes at work: one associated with massive star formation and one with that of solar-type stars. For this conference, the former is of less interest and I will concentrate on the latter.

The Internal Support of Molecular Clouds

To some extent the problem of star formation is actually not the collapse but the support mechanism (cf. *Woodward*, 1978). The maximum mass of a cloud with density, n, and temperature, T, that is stable against gravitational collapse is given by the Jeans mass

$$M_J = 30 \left[\frac{T}{10K}\right]^{1.5} \left[\frac{3\times10^2 cm^{-3}}{n}\right]^{0.5} M_\odot \qquad (1)$$

Thus, most molecular clouds are unstable against gravitational collapse unless supported by some other means than thermal pressure. The free-fall time scale for gravitational collapse is given by

$$\tau_{ff} = 2.6\times10^{6} \left[\frac{3\times10^{2}\ \mathrm{cm}^{-3}}{n}\right]^{0.5} \mathrm{yr} \qquad (2)$$

This is much shorter than the typical lifetime of molecular clouds ($\approx 3 \times 10^{7}$ yr) and therefore implies again an additional means of support. This is also evidenced by the observed linewidth of molecular rotational lines, which is typically about 1 km s^{-1} for dark clouds. In contrast, the thermal velocity dispersion of CO molecules at 10 K is only about 0.1 km s^{-1}. The additional linewidth is generally due to random motions (e.g., turbulence) rather than systematic motions (e.g., collapse or rotation). It is this turbulence that may support molecular clouds against gravitational collapse. Indeed, the virial mass implied by the linewidth and the observed mass of molecular clouds are in reasonable agreement (*Scoville and Sanders*, 1987; *Myers*, 1987; *Solomon et al.*, 1987).

One interesting suggestion that seems to be gaining ground is that molecular clouds are supported against collapse by magnetic fields (cf. *Shu et al.*, 1987; *Myers*, 1987; *Mouschovias*, 1987). Across the magnetic field the support is due to the magnetic pressure, while along the field it may be provided by Alfven waves. The required magnetic field strengths ($\approx 30\ \mu$G) are in reasonable agreement with observations of Zeeman splitting of HI and OH absorption lines in molecular clouds (*Heiles*, 1987; *Crutcher et al.*, 1987). For low-frequency waves, the Alfven velocity is given by

$$V_A = \left[\frac{B^2}{4\pi\rho}\right]^{0.5} \approx 0.4 \left[\frac{B}{30\mu G}\right]\left[\frac{3\times10^{4}}{n_H}\right] \mathrm{km\ s}^{-1} \qquad (3)$$

where ρ is the density of ions plus neutrals and B is the magnetic field strength. For a magnetically supported cloud, the Alfven velocity is therefore about equal to the virial velocity [$\sigma = \sqrt{(GM/R)}$].

A magnetic field, tied to the ionized component of the gas, behaves as a string under a tension $B^2/4\pi$ and will thus perform vibrations when slightly perturbed from rest. For an incompressible fluid those would be pure transversal vibrations both in an electromagnetic and a fluid mechanic sense (e.g., both **H** and **v** perpendicular to **k**). For a compressible fluid, however, these waves can become longitudinal in character, depending on the angle between **H** and **k** and the phase velocity of the wave (cf. *Parker*, 1979). In the limit that the sound velocity (≈ 0.4 km s^{-1} in molecular clouds) is much less than the Alfven velocity, these waves become purely hydromagnetic waves with velocity V_A in all directions.

Now, small disturbances introduced in the magnetic field in a conducting fluid are propagated away by the stresses in that field and fluid. In the interstellar case, the fluid is only weakly ionized. Nevertheless, the ions and neutrals are well coupled for long wavelength hydromagnetic waves and the phase velocity is given by the Alfven speed (cf. equation (3)). The (slow) contraction of a rotating cloud core (caused by ambipolar diffusion) will generate magnetic field distortions, which will excite Alfven waves. Inevitably, molecular clouds will be inhomogeneous and these inhomogeneities will also excite Alfven waves. Finally, the translational motion of a core within a molecular cloud will generate Alfven waves (*Mouschovias*, 1987). These Alfven waves, radiating from a core, stabilize the core and the surrounding molecular cloud against collapse. In this picture, the energy driving the turbulence is thus partly gravitational and rotational energy of the core. Additional turbulence in a molecular cloud is generated by clump-clump collisions (*Falgarone and Puget*, 1986) or shocks driven by protostellar winds (*Norman and Silk*, 1980). Note that torsional Alfven waves generated by the collapse of the rotating core will also transfer angular momentum from the core to the surrounding molecular cloud.

The damping time scale of these large-scale oscillations is essentially the ambipolar diffusion time scale. Collisions of a neutral with an ion occurs on a time scale

$$\tau_{ni} = [k\, n_i]^{-1} \approx 10^{4} \left[\frac{3\times10^{4}\mathrm{cm}^{-3}}{n_H}\right]\left[\frac{10^{-7}}{X_e}\right] \mathrm{yr} \qquad (4)$$

where k is the Langevin collision rate ($\approx 10^{-9}$ cm^{-3} s^{-1}; cf. *Herbst*, 1987). Thus, the shortest wavelength Alfven wave that can support a molecular cloud or the cores within a molecular cloud against gravitational contraction is given by (*Kahn*, 1974).

$$\lambda = 2\pi V_A \tau_{ni} \approx 6\times10^{16} \left[\frac{3\times10^{4}\mathrm{cm}^{-3}}{n_H}\right]^{1.5}\left[\frac{10^{-7}}{X_e}\right]\left[\frac{B}{30\mu G}\right] \mathrm{cm} \qquad (5)$$

Conversely, when a slowly contracting core (caused by ambipolar diffusion) approaches this size scale, ions and neutrals will decouple and rapid ambipolar diffusion will set in (*Mouschovias*, 1987). Star formation should thus be associated with dense cores with size scales in the range of about 0.1 pc, in agreement with observations of the Taurus cloud (cf. *Myers*, 1987). Note that for very-high-frequency, short-wavelength waves the Alfven velocity is given by equation (3) with ρ the ion density, which yields typically $V_A \approx 3 \times 10^{3}$ km s^{-1}. Thus, for wavelengths shorter than about 10^{13} cm (for typical core parameters) the plasma moves almost independently from the neutrals and their only effect is a slight damping of the waves. Intermediate wavelength Alfven waves cannot propagate in molecular clouds (*Kulsrud and Pearce*, 1969; *Zweibel and Shull*, 1983).

In summary, it is likely that molecular clouds are stabilized against collapse by magnetic fields and magnetic turbulence (Alfven waves). Probably, scattering and (partial) reflection of these waves at clump boundaries and inhomogeneities will lead to a rapid cascade of the turbulent energy to the shortest wavelength (e.g., equation (5)). The peaked CO line profiles typically observed imply that molecular clouds are macroturbulent on a small size scale (*Solomon et al.*, 1987; *Wolfire et al.*, 1988). We identify these turbulent "clumps" with the supporting Alfven waves. Assuming that the degree of ionization scales with $\sqrt{n_H}$ (cf. the section on Ion-Molecule Chemistry), the column density through such a clump corresponds to an A_v of about unity. Since typically a molecular cloud has an A_v of 10, there are about 10 of these Alfvenic clumps along any line of sight. Note that although these waves all move with the Alfven velocity, their line of sight velocity will be different. Therefore, they do not shadow each other in velocity space and will give rise to a peaked CO line profile (*Wolfire et al.*, 1988).

Fragmentation

The mass of a molecular cloud is much larger than that of newly-formed stars, which emphasizes the importance of fragmentation processes before or during the gravitational collapse. The importance of fragmentation can also be discerned from the large number of stars observed in close binaries with short periods. Probably, these formed from the fragmentation of one rotating clump. One important question to be answered by fragmentation theories is "Why do some stars form planetary systems while others fragment into double stars?" It is likely that the initial ratio of angular momentum to gravitational energy plays an important role in this (*Boss*, 1987). The angular momentum of a rapidly rotating cloud is converted in orbital angular momentum of fragments. In contrast, slowly rotating clouds collapse into a centrally condensed object with a surrounding planetary disk.

Hoyle (1953) suggested originally a hierarchical fragmentation scheme, where during the gravitational contraction smaller and smaller scales were supposed to become unstable and fragment out. This fragmentation process will stop once the collapsing fragments reach the adiabatic collapse phase and the pressure forces play an increasingly important role. The observed mass-size relationship of clumps in molecular clouds is very similar to that of molecular clouds themselves, lending support for hierarchical fragmentation at at least two levels. Numerical studies, however, show little support for hierarchical fragmentation (*Boss*, 1987). Moreover, observational studies of molecular clouds do not show the expected large-scale, collapse-velocity fields.

The problem of fragmentation has also been approached from the opposite direction. In that respect, consider a macroturbulent molecular cloud consisting of many small, supersonic clumps. Suppose that each contains less than a Jeans mass and therefore is stable against gravitational collapse. Because of its supersonic velocity, each fragment is ram pressure confined and will not expand. Such fragments may originate, for example, from the interaction of protostellar winds with the surrounding molecular cloud. Sweeping-up of interclump gas or coalescence of colliding clumps may then lead to Jeans unstable cloudlets and star formation (*Norman and Silk*, 1980).

Finally, particularly in view of the discussion in the preceding section, the effects of magnetic fields on the fragmentation process have to be considered. Although a magnetic field can temporarily support a molecular cloud, collapse will ultimately ensue. This is because neutrals dominate the mass of a molecular cloud and thus its gravitational field, but the magnetic field is coupled only to the ionized component. Since the degree of ionization is low in molecular clouds ($10^{-5} < X_e < 10^{-8}$), the neutral component can slip through the ionized component under the influence of its own self-gravity (ambipolar diffusion). The ratio of the ambipolar diffusion time scale, τ_{AD}, to the free-fall time scale, τ_{ff}, is given by (*Mouschovias*, 1987)

$$\frac{\tau_{AD}}{\tau_{ff}} \approx \frac{\tau_{ff}}{2\tau_{ni}} \approx 12\left[\frac{X_e}{10^{-7}}\right]\left[\frac{3\times10^4\mathrm{cm}^{-3}}{n_H}\right]^{0.5} \tag{6}$$

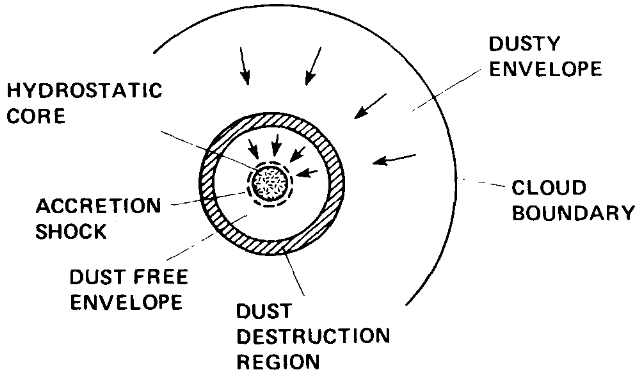

Fig. 2. A schematic picture of the structure of a spherically symmetric collapsing cloud (see text). Typical dimensions of this system are indicated in Table 1.

where τ_{ni} is the neutral-ion collision time scale (cf. equation (4)). Although not well founded in observations (cf. section on The Molecular Composition of Interstellar Clouds), the degree of ionization is often assumed to be about 10^{-7} in dense ($n \approx 3 \times 10^4$ cm^{-3}) molecular cloud cores. In that case, the ambipolar diffusion time scale is much longer than the free-fall time scale and the evolution of the cloud is magnetically determined. Since a dense core will lose its magnetic support on a shorter time scale than its surroundings, fragmentation of a magnetically supported cloud will result and ambipolar diffusion will lead to the quasistatic evolution of dense cores. Fragmentation will stop when Alfven waves can no longer support a core. This occurs typically for a size scale of about 10^{17} cm when the neutral-ion collision rate becomes longer than the critical Alfven frequency (cf. equation (5)). Ions and neutrals decouple at that point and a phase of rapid ambipolar diffusion will set in (*Mouschovias*, 1987). The minimum fragment mass is then about 0.1 $M_\odot$.

Structure of Protostars

The (one-dimensional) collapse of a spherically symmetric, nonrotating cloud is relatively simple to calculate. As a consequence, much theoretical work has been done on this idealistic (and unrealistic) problem and its characteristics are relatively well understood (cf. *Larson*, 1978; *Woodward*, 1978). The collapse of a cloud starts isothermally, but when the cloud becomes optically thick for the cooling radiation, it heats up. The collapse of a cloud is nonhomologous, i.e., the inside collapses faster than the outside. This results in a core-envelope structure in which the envelope falls freely in on a core, which is already in hydrostatic pressure equilibrium. At the interface, these two zones are separated by an accretion shock, which transforms nearly all of the kinetic energy of the infalling material into internal energy of the gas and almost completely radiates it away.

Generally the collapsing envelope will consist of two zones. In the outer zone, the opacity is dominated by the dust. In the inner zone, the dust has evaporated and the opacity, caused solely by the gas, is about 4 orders of magnitude less than in the outer zone. The two zones are separated by a sharp transition region where the dust evaporates. The evaporation temperature of graphite and amorphous carbon, the most refractory grain components thought to be present in the interstellar medium, is about 2000 K. Typically, this yields for the evaporation radius, R_{ev}, about 10^{13} cm. Figure 2 schematically shows the different zones in a collapsing cloud and Table 1 lists their approximate sizes.

TABLE 1. Sizes of the different zones in a collapsing spherically symmetric cloud.

Zone	r, cm
Central core	3×10^{10}
Accretion shock	3×10^{11}
Dust-free envelope	10^{13}
Dusty envelope	10^{17}

Many hydrodynamic studies have been performed on the collapse of rotating clouds. Most of these were, however, concerned with the development of different types of instabilities (e.g., the fragmentation process; cf. *Boss*, 1987). As a result of the increase in complexity, only a few hydrodynamic collapse calculations have been performed on which the collapse is followed all the way to stellar densities (cf. *Tscharnuter*, 1985). Obviously, the collapse will be somewhat different than described above for the one-dimensional case. In particular, the collapse will be faster along the rotation axis than perpendicular, leading to a flattened density distribution. In the center a core surrounded by a circumstellar disk will form. Again this will be surrounded by a freely-falling envelope, containing a dust-free and a dusty zone separated by a sharp evaporation region. There will be an accretion shock on the disk as well as the core. As a result, there will be a range of shock velocities, depending on the position in the disk. Figure 3 schematically shows the different zones in a collapsing rotating cloud and Table 2 lists some typical parameters. Note that in the astronomical literature the term "circumstellar disk" often refers to the (flattened) envelope

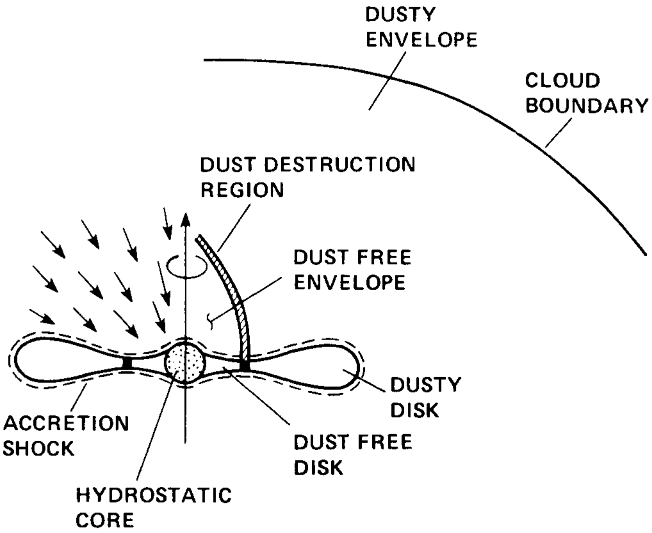

Fig. 3. A schematic picture of the structure of a collapsing, rotating cloud (see text). Typical dimensions of this system are indicated in Table 2.

TABLE 2. Sizes of different zones in a collapsing rotating cloud.

Zone	R,cm
Central core	3×10^{10}
Dust-free disk	10^{13}
Dusty disk	10^{14}
Dust-free envelope	10^{13}
Dusty envelope	10^{17}

falling in on the protostar and its surrounding planetary disk. For comparison reasons, the highest resolution in CO observations is about 5" with interferometers. This corresponds to a linear size scale of about 0.004 pc ($\approx 10^{16}$ cm $\approx$ 750 AU) at the Taurus cloud, the nearest site of star formation. Such observations thus mainly probe the collapsing envelope. For very bright sources IR speckle techniques can obtain somewhat higher resolution ($\approx$ 0.3" $\approx 2 \times 10^{-4}$ pc $\approx$ 50 AU) and can thus resolve the inner, infalling, dusty envelope.

The mass in the disk, relative to that in the core, is very sensitive to the ratio of the accretion rate to the angular momentum transport rate in the disk (*Cassen and Summers*, 1983). Thus, the thin disk model of *Lin* (1981) and the fat disk model of *Cameron* (1978) for the protoplanetary disk around the early sun are characterized by small and large ratios, respectively. This difference also bears directly on the basic problem of planet formation. In a thin disk model, planet formation starts with the nucleation, condensation, and clustering of small dust grains. These will settle in a thin dust disk. Agglomeration processes in this dust disk then ultimately build up the planets. In contrast, in a fat disk model, planet formation is initiated by gravitational instabilities in the disk. In this way, dense clumps are formed that contract upon themselves and form the planets. It is beyond the scope of this review to comment on the pros and cons of these different scenarios for planet formation and the reader is referred to several discussions in the literature (cf. *Black and Matthews*, 1985).

Outflows

The presence of strong stellar winds in T-Tauri stars was suggested as early as 1962 on the basis of the P Cygni profiles of Hα in some T-Tauri stars (*Herbig*, 1962). The best evidence for mass-loss from T-Tauri stars comes from molecular observations. CO observations in the vicinity of T-Tauri stars and other pre-main-sequence, low-mass stars reveal blue and red shifted emission in two opposing lobes (*Snell and Edwards*, 1981). The observed CO outflow velocities in these low-mass stars are of the order of 15 km s^{-1} or less. Evidence for outflow is also seen in the motion of Herbig-Haro (HH) objects associated with low-mass protostars. Proper motion studies and emission line studies reveal much higher velocities, up to 400 km s^{-1} (cf. *Schwartz*, 1985). Generally, HH objects are the brightest knots of a larger scale emission system (i.e., optical jets) with a similar spectrum (*Mundt et al.*, 1987). These jets show a much higher degree of collimation (5°–10°) than the CO outflows ($\approx$ 50°). Figure 4 shows a schematic picture of the outflow around low-mass protostars. At this point, the morphological similarities between these stellar jets and their "big brothers" in active galactic nuclei is worth pointing out (cf. *Henriksen*, 1986), although differences in velocities, collimation, and temperature rule out a single outflow mechanism.

The picture that emerges from the wealth of data available is one of protostars losing mass at a high rate and a significant fraction of the stellar mass ($\approx$ 0.2 $M_\odot$) can be ejected in 10^5 years. However, the nature of the stellar wind is not well known. Possibly a fast isotropic wind originates from the stellar surface. This stellar wind is channeled, quite close to the star, into two opposing lobes, possibly by a circumstellar disk (i.e., collapsing envelope). These interactions would give rise to rather wide opening angles. The stellar wind blows an expanding bubble in the molecular cloud. The impact of the stellar wind on the surrounding molecular cloud material causes two shocks to occur (cf. Fig. 4). First, the wind itself will shock against a shell of swept-up material (stellar wind shock; v $\approx$ 100 km s^{-1}). Second, this shell of swept-up material will be driven supersonically into the molecular cloud (i.e., the molecular shock; v $\approx$ 15 km s^{-1}). CO observations show little evidence for a high-velocity molecular outflow, and radio observations do not reveal a strong ionized component; thus the stellar wind has to be predominantly neutral and atomic. The interaction of the fast stellar wind with dense clumps in the surrounding material gives rise to bow shocks, which are the HH objects in this picture. The difference in confinement between the CO flows and the optical jets (e.g., HH objects) is, however, difficult to understand in this model.

Alternatively, the optical jets represent collimated, steady flows of very tenous gas at very high velocity. This jet impacts on the surrounding cloud at the "working surface" where a strong shock develops (cf. *Blandford and Rees*, 1974). This slows the outflowing gas down and forces it outwards and backwards in the direction of the jet opening. This material forms a hot, turbulent cocoon around the jet, which will expand into the surrounding molecular cloud material. Near the boundary these turbulent vortices cause some of the ambient gas to be entrained into the flow in the cocoon. Bow shocks associated with the working

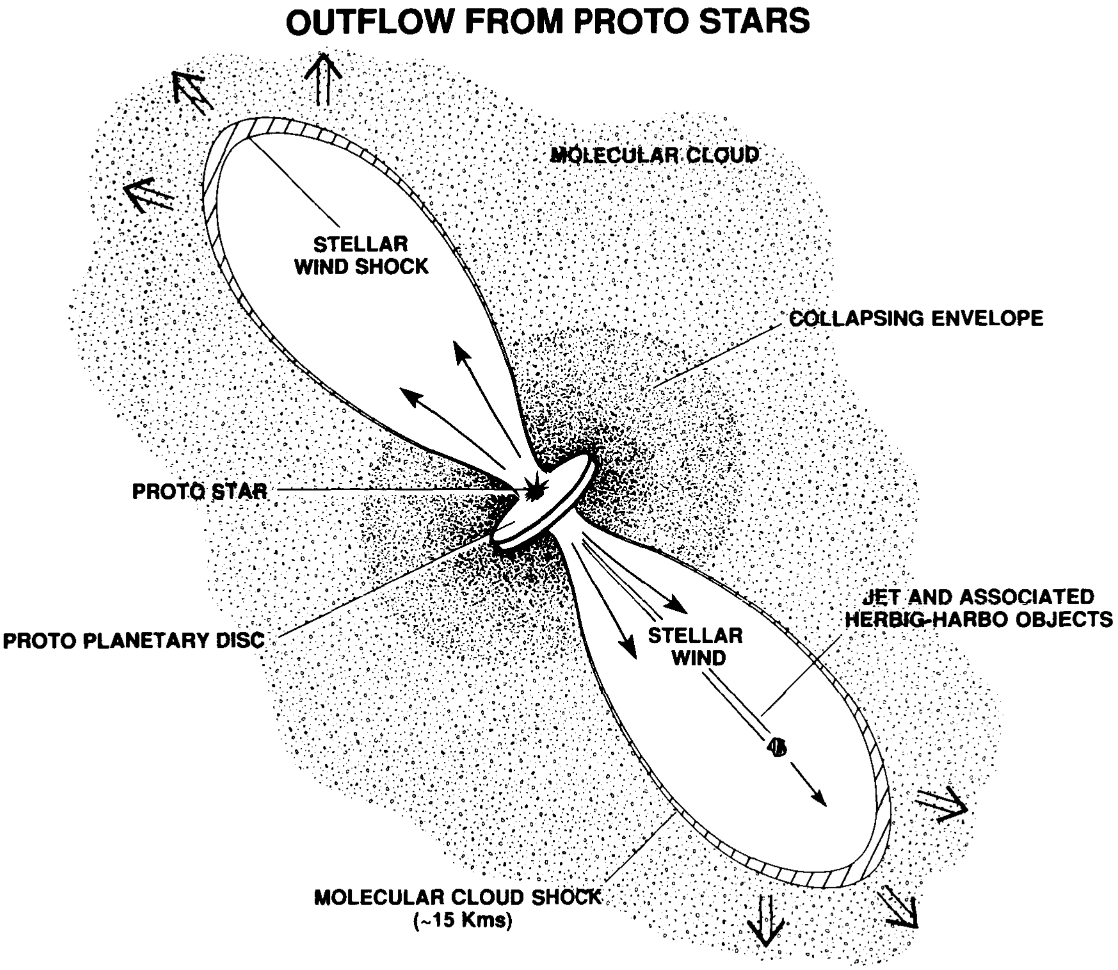

Fig. 4. A schematic picture of stellar wind driven by a protostar (adapted from *Snell et al.*, 1980). See text for details.

surface as well as instabilities in a confined, highly supersonic flow (e.g., oblique shocks) will give rise to shock emission lines (e.g., HH objects; *Mundt et al.*, 1987). The initial confinement of the optical jets is, however, still an open question in this model, although magnetic fields are likely to play a large role in this.

The energy source that powers protostellar outflows is also not well understood. Most models proposed convert rotational energy of the collapse or the protostar into outflow energy, often through magnetic fields. For example, the outflow may be generated by the redistribution of angular momentum in the newly formed star when the star goes from radiative (fast rotator) to convective (slow rotator; *Shu and Tereby*, 1984). Stellar activity, such as flares, may play a major role in the acceleration of the high-velocity, highly collimated jets. Indeed, one might think that large coronal holes provide the initial small opening angle of the optical jets. Many protostellar objects show stellar activity as evidenced by chromospheric lines, variability, and X-ray observations (*Giampapa and Imhoff*, 1985). As in the case of the sun, magnetic field line reconnection driven by deep convective zones may accelerate electrons and protons to high velocities and their outflow would then be tied to magnetic field lines.

From this discussion it is obvious that the jury is still out on the outflow mechanism. Although either of these two classes of models has some good points working for it, neither of them seem to be able to explain all the details of the outflow. Perhaps a hybrid variant will succeed.

GRAINS, CHEMISTRY, AND THE EARLY SOLAR SYSTEM

In recent years it has increasingly become clear that the heavy elements have had a long and complex chemical history before becoming part of the solar system. The evolution of these elements starts with their nucleosynthetic formation inside stars followed by their ejection either in solid or in gaseous form into the interstellar medium during the later stages of stellar evolution (e.g., late-type giants, planetary nebulae, novae, and supernovae). These species and compounds are subsequently modified by physical and chemical processes, such as UV photon irradiation, gas phase chemistry, accretion and subsequent reaction on grain surfaces, cosmic ray bombardment, and shock processing, as they are continuously recycled between diffuse and dense clouds in the interstellar medium. Understanding the interplay between this evolution and the formation of the solar system is one of the major unexplored problems in star formation studies. In this section we will discuss the current understanding of the molecular composition of interstellar clouds with the emphasis on the molecular processes involved (see section on The Molecular Composition of Interstellar Clouds). An appreciable fraction of the heavy elements is tied up in solid dust grains. Their formation and evolution is briefly discussed in the section on Interstellar Dust. In the section on Interrelationship, the interrelationship between interstellar and interplanetary dust is briefly examined.

THE MOLECULAR COMPOSITION OF INTERSTELLAR CLOUDS

Observations have revealed a wealth of molecules inside interstellar molecular clouds. Table 3, taken from *Irvine et al.* (1987), lists the molecules detected up to about 1987. The large number of ions, radicals, and unsaturated molecules identified is particularly noteworthy. Clearly, the chemical composition of interstellar clouds is far from chemical equilibrium and attests to the importance of ion-molecule gas phase chemistry (*Irvine et al.*, 1987). Nevertheless, to a much larger extent than before, it is now realized that the gas phase composition of molecular clouds is the result of the complex interplay of many diverse chemical processes. These include ion-molecule and neutral-neutral gas phase reactions and grain surface and grain bulk reactions in quiescent clouds, shock chemistry in protostellar outflow regions, as well as the survival of molecules originally produced in the outflow from late-type red giants. Each of these processes may contribute and in some regions even dominate the chemical composition in the gas phase.

Ion-Molecule Chemistry

Inside dense molecular clouds ion-molecule reactions are driven by cosmic-ray ionization, while at the cloud surface UV photons may play an important role. In contrast to many neutral-neutral reactions, ion-molecule reactions generally have no activation barrier. Moreover, because of the Coulomb interaction, the rate coefficients of ion-neutral reactions are much larger ($k \approx 10^{-9}$ cm^3 s^{-1}) than for neutral-neutral reactions ($\approx 10^{-12}$ cm^3 s^{-1}). Ions can, therefore, play a dominant role in interstellar chemistry despite the low degree of ionization [$X(\text{ion}) \approx 10^{-3} \times (\text{CO})$]. One important signature of ion-molecule reactions is the production of ions and radicals, such as HCO^+, OH, and C_2H. Cosmic-ray ionization of the most abundant molecule, H_2, will produce H_2^+, which will further react to form H_3^+. This molecule forms a cornerstone in the ion-molecule scheme. Reactions with abundant, neutral atoms and molecules will form more complex ions and subsequent dissociative electron recombination reactions will produce larger neutral species. As an example, consider the following sequence, which converts atomic oxygen into its hydrides OH and H_2O

$$O \xrightarrow{H^+{}_3} H_2O^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{e^-} H_2O{,}OH$$

These neutrals or their protonated counterparts can then react with C^+ or C to ultimately yield CO, the most abundant molecule after H_2

$$C^+ \xrightarrow{H_2O} HCO^+ \xrightarrow{e^-} CO$$

and

$$C \xrightarrow{OH} CO$$

Note that the latter is actually a neutral-neutral reaction. Such reactions between atoms and radicals generally possess no activation barrier and can be important for the synthesis of neutral molecules.

Because of a small zero-point energy difference ($\approx$ 180K), the H_2D^+/H_3^+ ratio will be enhanced at low temperatures ($\approx$ 10K) by many orders of magnitude over the cosmic ratio of D/H ($\approx 10^{-5}$). This will lead to large deuteration effects in daughter molecules, such as HCO^+ and N_2H^+, resulting from the reaction of abundant neutral molecules with H_2D^+. Indeed, in cold dense molecular clouds the DCO^+/HCO^+ ratio is observed to be typically about 0.1. Thus, although the pivotal molecule H_3^+ has not yet been detected, the presence of many radicals and ions as well as the large deuteration effects observed provide general support for the importance of ion-molecule chemistry in molecular clouds (cf. *Prasad et al.*, 1987; *Langer*, 1985).

Because of its importance in the coupling to magnetic fields, it is appropriate to discuss the degree of ionization inside dense clouds inferred from observations. In the past, observations of DCO^+/HCO^+ have been used to infer very low electron abundances inside dense molecular clouds ($<10^{-8}$ with respect to H; *Guelin et al.*, 1977). Among other

TABLE 3. Interstellar molecules.

Simple hydrides, oxides, sulfides, and related molecules			
H_2	CO	NH_3	CS
HCl	SiO	SiH_4^{*}	SiS
	H_2O	CH_4^{*}	OCS
	SO_2		H_2S
	CC		HNO ?
Nitriles, acetylene derivatives, and related molecules			
HCN	$HC{\equiv}C{-}CN$	$H_3C{-}C{\equiv}C{-}CN$	$H_3C{-}CH_2{-}CN$
H_3CCN	$H(C{\equiv}C)_2{-}CN$	$H_3C{-}C{\equiv}CH$	$H_2C{=}CH{-}CN$
CCCO	$H(C{\equiv}C)_3{-}CN$	$H_3C{-}(C{\equiv}C)_2{-}H$	$HN{=}C$
$HC{\equiv}CH^{*}$	$H(C{\equiv}C)_4{-}CN$	$H_3C{-}(C{\equiv}C)_2{-}CN$	$HN{=}C{=}O$
$H_2C{=}CH_2^{*}$	$H(C{\equiv}C)_5{-}CN$		$HN{=}C{=}S$
Aldehydes, alcohols, ethers, ketones, amides, and related molecules			
$H_2C{=}O$	H_3COH	$HO{-}CH{=}O$	H_2CNH
$H_2C{=}S$	H_3CCH_2OH	$H_3C{-}O{-}CH{=}O$	H_3CNH_2
$H_3C{-}CH{=}O$	H_3CSH	$H_3C{-}O{-}CH_3$	H_2NCN
$NH_2{-}CH{=}O$		$H_2C{=}C{=}O$	
Cyclic molecules		*Ions*	
C_3H_2		CH^+	HCS^+
SiC_2		H_2D^+ ?	$HCNH^+$
		HN_2^+	SO^+
		$HOCO^+$	HOC^+ ?
			HCO^+
Radicals			
CH	C_2H	CN	HCO
OH	C_3H	C_3N	NO
	C_4H	NS	SO
	C_5H		

*Detected only in the envelope around the evolved star IRC+10216.
?Claimed but not yet confirmed.

things, this was based on the assumption that dissociative electron recombination is one of the dominant destruction mechanisms of the precursor ions H_2D^+ and H_3^+. Since then it has been shown that several of the key assumptions used to derive this number are incorrect (cf. *Langer*, 1985). For example, recent laboratory studies have shown that the rate of the dissociative electron recombination reaction of H_3^+ in the ground vibrational state is exceedingly small and that this reaction is of little importance for the abundance of interstellar H_3^+ (*Smith and Adams*, 1984). Consequently, only very unrestrictive upper limits ($X_e < 10^{-5}$; *Langer*, 1985) can be placed on the electron abundance by this method. Of course, the degree of ionization has to be larger than the measured abundance of the positive ions, such as HCO^+ and its isotopes. This yields typical lower limits of about 10^{-8} for the degree of ionization (*Langer*, 1985). An estimate (or more correctly, an upper limit) for the electron abundance can be inferred from the measured HCO^+ abundance by balancing ionization of H_2 (which is passed on to molecular ions through H_3^+) with recombination of HCO^+. Assuming an H_2 ionization rate, $\zeta = 5\times10^{-17}\,s^{-1}$, which is typical for diffuse interstellar clouds, yields then $X_e \lesssim 3\times10^{-7}$ (*Langer*, 1985). However, the ionization rate inside dense molecular clouds may actually be quite different from that in diffuse clouds. Thus, although it is likely that the degree of ionization is of the order of 10^{-7}, substantially different values cannot be excluded.

Theoretically, it is expected that the ionization by cosmic rays of H_2 is rapidly transferred to molecular and metal ions. Because of their much smaller electron recombination rates (radiative rather than dissociative as for molecular ions), metal ions are the dominant cations in molecular clouds despite their low elemental abundance (*Oppenheimer and Dalgarno*, 1974; *Prasad and Huntress*, 1980). The degree of ionization is then governed by the metal depletion in and on grains. Often, in particular in MHD studies of cloud collapse, the degree of ionization is assumed to be given by (cf. *Elmegreen*, 1979)

$$X_e = 10^{-7}\left[\frac{3\times10^4\,cm^{-3}}{n_H}\right]^{0.5} \tag{7}$$

where the density scaling follows from balancing cosmic-ray ionizations with recombinations and the absolute value is effectively a fit to (often old) interpretations of DCO^+

observations. This is dangerous assumption, not only because of the (recent) difficulties in the analysis of the observations, but also because of the neglect of other processes that may play a role. These include accretion of gas phase species on grain surfaces. Ionization by the ambient interstellar UV radiation field can also be important (*McKee*, 1987) when A_v is less than about 10 magnitudes. Typically, the visual optical depth through a molecular cloud is about 10 magnitudes (*Myers*, 1987). Care should thus be taken in using these generic laws.

Grains and the Gas Phase Composition of Molecular Clouds

Grain surface reactions can also play an important role in the formation of gas phase molecules. It is difficult to form H_2, the most abundant gas phase molecule, through reactions in the gas phase and the general consensus is therefore that H_2 is formed by atomic hydrogen recombination on grain surfaces. Because of its low binding energy to grain surfaces, the newly formed, "hot" H_2 is either ejected immediately upon formation or will rapidly thermally evaporate after equilibration with the grain. The contribution of grain surface reactions to the abundance of other gas phase molecules is more controversial. Typically, grain surface reactions will lead to simple saturated molecules such as H_2O, NH_3, and CH_3OH (*Tielens and Allamandola*, 1987a). Indeed, IR observations show that these molecules are the most abundant molecules in the solid state (*Tielens and Allamandola*, 1987b). Their binding energy to grain surfaces is, however, much larger than that of H_2 and at a typical grain temperature of 10K thermal evaporation is negligible. More exotic ejection mechanisms are required to produce an appreciable contribution to the gas phase composition of molecular clouds.

One such mechanism may be UV photolysis of icy grain mantles, producing simple radicals such as H, OH, and HCO. These radicals cannot diffuse in the icy matrix at low temperatures (<30K) and a small concentration (≈ 1%) of these reactive species can be built up. Upon gentle warmup to about 30K these stored radicals will start to diffuse and react among each other. The released heat of reaction can then lead to "explosive" evaporation, which releases a large fraction of the icy grain mantle into the gas phase (*d'Hendecourt et al.*, 1986). These "explosions" can be triggered by the heat deposition due to Fe cosmic-ray interactions with the grain mantle or due to low-velocity, grain-grain collisions (*Leger et al.*, 1985; *d'Hendecourt et al.*, 1982). Note that since most of the diffusing radicals will react, an appreciable amount of larger saturated molecules can be formed. Such complex molecules may remain on the grain after the explosion and form an organic refractory grain mantle with a polymeric structure (*Greenberg*, 1982; *Tielens and Allamandola*, 1987a). The efficiency of this process is not known but might be as high as 10^{-4} of all the molecules in the icy grain mantle. However, in contrast to ion-molecule gas phase chemistry, grain surface and UV photolysis of icy grain mantles will mainly lead to the formation and ejection into the gas phase of simple saturated molecules such as H_2O, NH_3, and CH_3OH.

While hydrogen is mainly in the form of H_2 inside molecular clouds, atomic deuterium can contain a large fraction of the available elemental D abundance. As a consequence the ratio of atomic D to atomic H can be much larger than the elemental abundance ratio. Upon accretion on grain surfaces this will lead to large deuteration effects in the newly formed hydrides. Theoretical studies indicate, for example, that the HDO/H_2O ratio in interstellar icy grain mantles can be as large as 0.1. A high abundance of simple, saturated, deuterated molecules in the gas phase may therefore be an indicator of the importance of grain surface chemistry to the gas phase composition of molecular clouds (*Tielens and Allamandola*, 1987a).

Recent studies of the hot core in Orion have provided for the first time direct support for the contribution of grain chemistry to the gas phase composition of molecular clouds. The high abundance of simple saturated hydrides, such as NH_3 and CH_3OH and, in particular, the deuterated molecules HDO and NH_2D, in this warm gas is difficult to explain using gas phase molecule formation schemes. It is now generally thought that these molecules have been formed on grain surfaces and have recently (<10^4 yrs) been released into the gas phase due to the sudden turn-on of the luminous, protostar IRC2 (*Sweitzer*, 1978; *Walmsley et al.*, 1987; *Blake et al.*, 1987).

Shock Waves and the Molecular Composition of Molecular Clouds

Strong shocks can influence the composition of molecular clouds because they lead to large column densities of warm atomic and molecular gas or because they lead to large drift velocities between ions and neutrals. Shocks come in two varieties: the J and C shocks. J shock fronts consist of a narrow transition zone where the global kinetic energy is transformed into internal energy of the gas on a collision length scale. The density, pressure, and temperature thus show a sudden jump (hence the name J shock). The high kinetic temperature will allow reactions with appreciable activation barriers or even endothermic reactions to occur and a gas phase composition very different from that produced by low-temperature ion-molecule reactions may ensue. A nondissociative J shock (V<25 km s^{-1}) converts simple neutral atoms and molecules in their hydrogenated counterparts (e.g., O into H_2O; N into NH_3) as well as other molecules (e.g., SO, HCN). Another signature of shocked gas is, of course, the enhanced temperature as well as the dynamical information contained within line profiles. Higher velocity shocks will lead to molecular dissociation. Because of the long reformation time scale of H_2 compared to the cooling time scale, molecule formation is then generally inhibited in the warm gas.

C-type shocks may form in a magnetized molecular cloud when the ionized fraction is low. Because of their weak coupling, the electron and ion flow velocities and temperatures can differ appreciably from those of the neutrals. The charged particles will stream ahead as a magnetic precursor. Dissipation of energy in this precursor through radiation can be so great that the neutral shock becomes a continuous transition (hence the name C shock) rather than a jump (*Shull and Draine*, 1987). Because the temperature is much lower, endothermic neutral-neutral reactions are less important in a C shock than in a J shock of the same speed. However, ion-neutral reactions can be driven by the large ion-neutral drift velocities. It is likely that the warm H_2, CO, OH, SiO, SO_2, SO, and H_2S in the BN-KL Orion source is due to the propagation of a 35 km s^{-1} C shock into a molecular cloud with a density of about 10^5 cm^{-3} (*Chernoff et al.*, 1982; *Draine and Roberge*, 1982). Similarly, the high abundance of CH^+ in diffuse clouds may also result from a C shock (*Draine and Katz*, 1986).

PAHs in Molecular Clouds

Finally, it is possible that some complex molecules generated in the "hot" regions (≈ 1000 K) around late-type giants are sufficiently stable to survive for an appreciable time in the diffuse interstellar medium. Arguments for a contribution of circumstellar shells to the molecular complexity of the interstellar medium have been

TABLE 4. Interstellar dust components.

Component	Structure	Birth Site	Elemental Abundance*	Rel. Volume†	Spectral Signature	Ref.
Silicates	Amorphous	O-rich giants & novae	100% Si, 20% O (Mg & Fe?)	1	10,20 μm features	1,2 3
Graphite	Crystalline	C-rich giants (?)	≥ 25%C	≥ 0.25	2200Å bump**	3,4 5,6
Polycyclic aromatic hydrocarbons	Molecular species	C-rich planetary nebulae	1% C	0.01	3.3, 6.2 7.7, 11.3 μm emission	7
Amorphous carbon	Poly-crystalline	C-rich giants	5–10% C	~0.08	7.6μm absorption	3,8
Icy grain mantles§	Amorphous	Molecular clouds	up to 40% C and O§	up to 2.8§	3.1, 4.6, 6.0, 6.85μm absorption	3,8
Organic refractory grain mantle	Amorphous polymer	Interstellar medium	24%C 6% O¶	~0.8¶	3.4, 6.0μm absorption	3,9
SiC	Crystalline	C-rich giants & planetary nebulae	–‡	–‡	11.4 μm emission	10,11
MgS	Crystalline	C-rich giants & planetary nebulae	–‡	–‡	30μm emission	12

*Percentage of cosmic abundance of element locked up in interstellar dust component.
†Volume of dust component relative to that of silicates.
‡This dust component not (yet) detected in interstellar medium.
§This dust component ubiquitous in molecular clouds—not observed in diffuse interstellar medium.
¶This dust component only observed toward galactic center (it is presumed more widespread).
**Only graphite grains of~ 200Å contribute to this bump.

References: (1) *Merrill* (1977); (2) *Aitken* (1981); (3) *Tielens and Allamandola* (1987a); (4) *Savage and Mathis* (1979); (5) *Gilra* (1973); (6) *Tielens and de Jong* (1979); (7) *Allamandola et al.* (1985); (8) *Tielens et al.* (1987a); (9) *Tielens et al.* (1987b); (10) *Cohen and Treffers* (1974); (11) *Cohen* (1984); (12) *Goebel and Moseley* (1985).

presented in the case of cyanoacetylenes, cyanopolyynes, and polycyclic aromatic hydrocarbons (PAHs; *Douglas*, 1977; *Allamandola et al.*, 1985). The latter will be discussed in the next section. The most important destruction process for such molecules is UV photodissociation. For large molecules internal conversion of the electronic excitation to high vibrational levels and its distribution among all the possible vibrational modes is expected to be very rapid. This can essentially inhibit dissociation since the molecule may emit the UV photon energy in the IR through vibrational transitions (*Douglas*, 1977; *Allamandola et al.*, 1985). For example, it has been calculated that a 20 C atom PAH molecule will not even lose peripheral H atoms upon absorption of a 1000 Å photon (*Tielens et al.*, 1987). Photoisomerization may, however, play an important role for such molecules and thus strictly speaking the molecular identity of the circumstellar molecule may change in the ISM.

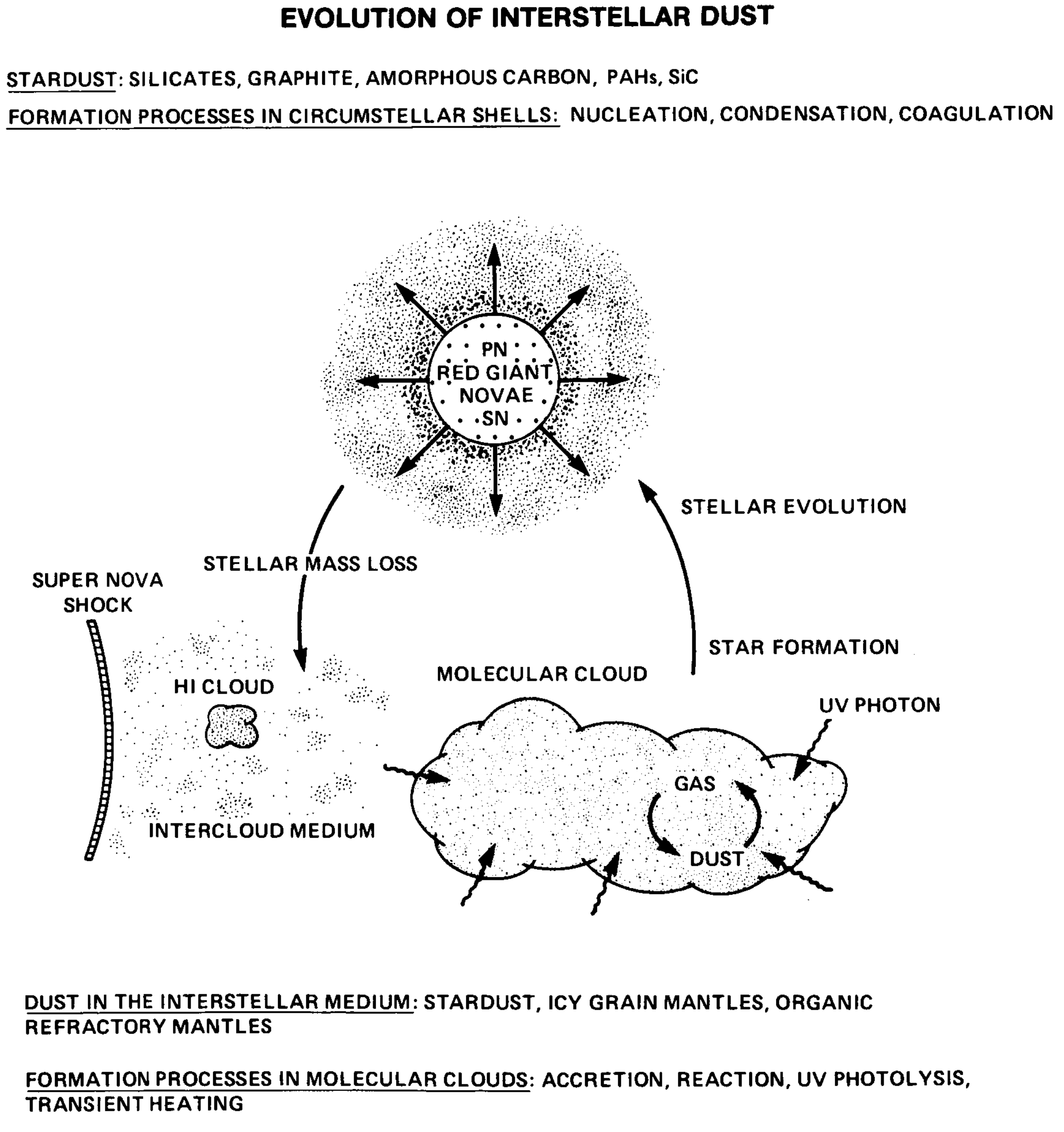

Fig. 5. A schematic representation of the evolution of interstellar dust (taken from *Tielens and Allamandola*, 1987b). The processes that play a role in the formation and evolution of interstellar dust are summarized in the figure. Stardust is formed in the outflow from stars in the later phases of their evolution and ejected into the interstellar medium. Interstellar medium dust is formed inside dense molecular clouds. Dust is destroyed by strong supernova shocks and by incorporation into newly formed stars.

INTERSTELLAR DUST

Interstellar dust consists of many different components, including amorphous silicate, graphite, PAHs, amorphous carbon, icy grain mantles, and organic refractory grain mantles. Silicon carbide and magnesium sulfide, which have been identified in the outflow from carbon-rich giants and planetary nebulae, might also be present in the interstellar medium. Our present knowledge on the composition of the interstellar dust is summarized in Table 4. For each component, this table gives the structure, birth site, fraction of the elements that it locks up, and volume relative to that of silicates. The spectral signatures that have been used to identify each dust component are also indicated. For a discussion of these the reader is referred to *Tielens and Allamandola* (1987a) as well as to earlier reviews (*Merrill*, 1977; *Aitken*, 1981; *Willner*, 1984). Note that this table lists only those dust components for which there is astronomical evidence for its existence. Interstellar dust components inferred from studies of meteorites (e.g., diamonds) have not been included.

The evolution of the dust is determined by many complex interplaying processes whose details are not very well understood. Figure 5 gives a schematic overview of the evolution of interstellar dust. Some dust components (e.g., silicates, graphite, and amorphous carbon) are formed in the outflow from stars in the later stages of their evolution (e.g., red giants, planetary nebulae, novae, and supernovae). Physical processes that play a role in the formation of this so-called stardust include nucleation, condensation, clustering, and coagulation. In contrast, other components (e.g., icy and organic refractory grain mantles) are formed in the interstellar medium by accretion, reaction, UV photolysis, and transient heating processes (so-called interstellar medium dust). Finally, dust is also modified and destroyed by supernova shock waves in the interstellar medium. Processes that are thought to play an important role in this include sputtering by impacting gas atoms and grain-grain collisions. The latter can lead to vaporization, shattering, and high-pressure metamorphism (e.g., diamond formation; *Tielens et al.*, 1987). The formation of icy grain mantles and their evolution into organic refractory grain mantles has already been touched upon in the section on The Molecular Composition of Interstellar Clouds. Here we will concentrate on the possible presence of PAHs.

A wide variety of objects (planetary nebulae, HII regions, reflection nebulae, and galactic nuclei) show strong, relatively broad emission features at 3.3, 6.2, 7.7, and 11.3 μm as well as a host of weaker features. Although some of the detailed assignments are controversial, it is generally agreed that the major emission features are due to CH and CC stretchings and bending modes of aromatic materials. The emission in the 3.3-μm feature relative to that in the 11.3-μm feature is fairly constant from source to source and within sources. The absence of temperature variations, despite the widely varying physical conditions, has been taken to imply that the emission is due to a single photon event. That is, after the absorption of one UV photon, the excited species completely relaxes before absorption of the next. Moreover, the excitation "temperature" as measured by the 3.3/11.3-μm ratio is observed to be very high even at considerable distances from the illuminating star in reflection nebulae. Since the excitation energy is limited to nonionizing UV photons (<13.6 eV), this can be used to constrain the size of the emitting species. Analysis of the observations implies then carriers containing 20 to 50 C atoms (*Leger and Puget*, 1984; *Allamandola et al.*, 1985). Such small aromatic species are actually large polycyclic aromatic hydrocarbon molecules (PAHs) rather than small dust grains. it should, however, be emphasized that spectroscopically it is very difficult to distinguish between a collection of PAH in the form of free flying molecules from that in the form of a solid dust particle (e.g., soot) and the *only* evidence pointing to PAH molecules rather than soot lies in the excitation mechanism (*Allamandola et al.*, 1987).

INTERRELATIONSHIP

One of the most interesting developments within the field of interstellar dust in recent years is the realization that some interstellar grains may have been incorporated into meteorites and interplanetary dust particles without totally losing their identity (cf. the review by *Kerridge*, 1986). Evidence for this rests on the measurement of isotopic anomalies in meteorites and in particular in carbonaceous chondrites. Although the meteoritic composition is in a global sense remarkedly homogeneous, non-mass-dependent isotopic anomalies do exist for many elements. These include the noble gasses, the light elements (H, C, N, and O), and the heavy elements (e.g., Ca, Ti, Cr, Ni, Nd, Sm, and others). Although some unusual process in the solar nebula might have produced non-mass-dependent isotopic fractionation in some elements, it is unlikely that it could account for all of them. Moreover, the measured isotopic anomalies are very characteristic for a presolar origin of the material. For example, the Xe and Kr isotopic anomalies associated with meteoritic kerogen carry the signature of s processes in red giants, suggesting the presence of largely unmodified carbon grains in meteorites that were produced in carbon-rich red giant outflows (cf. *Kerridge and Chang*, 1985). Thus, meteoritic materials carry a nucleogenic record of the birth site of the dust grain, modified by processes that occurred in the interstellar medium as well as in the solar nebula or on planetary bodies. Consequently, laboratory analysis of meteoritic and interplanetary material may yield detailed microscopic information on interstellar dust, which is not obtainable by astrophysical observations. It should, however, be emphasized that meteoritic materials are very heterogeneous and contain dust grains from different origins, including star dust from many different birth sites, interstellar medium dust, and solar nebula condensates. Generally, the actual presolar carrier of the measured isotopic anomalies is not known. Such information is, however, of prime importance for our reading of this record and for our assessment of the implications for interstellar dust and its evolution.

One of the principal observational pieces of evidence for the presence of some interstellar, as distinct from circumstellar, material in meteorites lies in the high D/H values measured in several organic fractions of carbonaceous and other primitive chondrites (*Geiss and Reeves,* 1981; *Kerridge and Chang,* 1985). The observed enrichments, up to a factor of about 40, implicate chemical fractionation, in particular fractionation due to the difference in zero-point energy between deuterated species and their hydrogenated counterparts. The low temperature (<150K) required for this chemical fractionation process implies that neutral-neutral reactions are too slow to produce the measured deuterium fractionations within the solar nebula (*Lewis and Anders,* 1983). Moreover, it is likely that the temperature in the asteroid belt of the solar nebula, the origin of the meteoritic material, was generally much higher than 150K (*Lewis,* 1974). Since high deuterium fractionations are easily obtained at the low temperatures of the interstellar medium (cf. the section on The Molecular Composition of Interstellar Clouds), the hypothesis that deuterium-enriched organic molecular material, synthesized in the parental, interstellar, molecular cloud of the protosolar nebula and subsequently incorporated into carbonaceous meteorites, has been widely accepted (cf. the review by *Kerridge and Chang,* 1985).

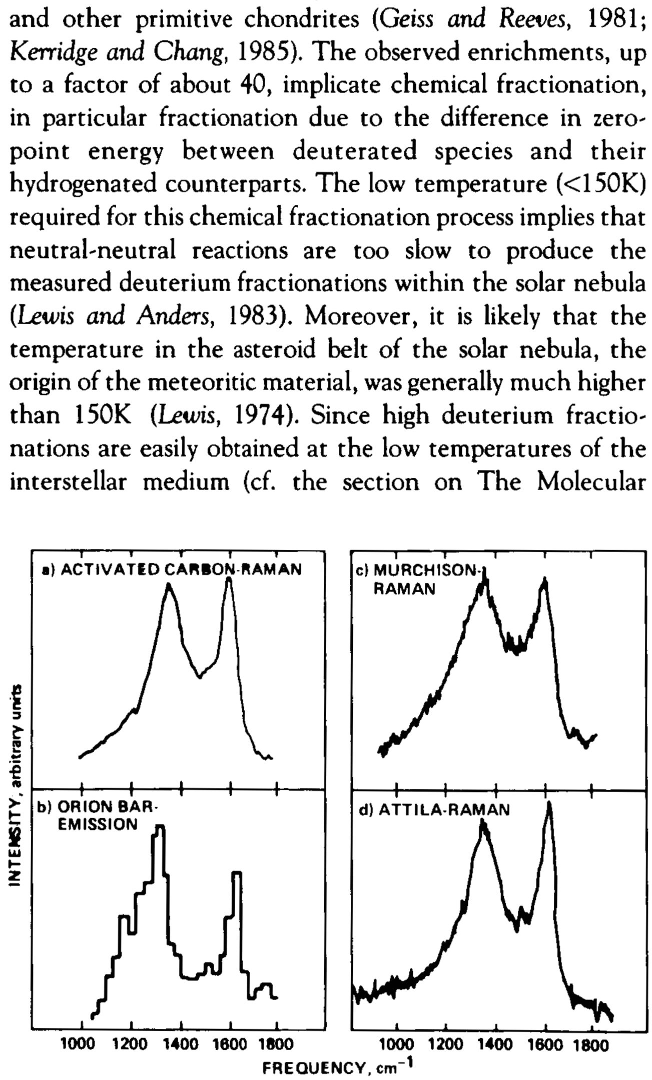

Fig. 6. A comparison of the Raman spectrum of activated carbon (soot), the Murchison meteorite, and an interplanetary dust particle (Attila) and the infrared emission spectrum observed toward the Orion bar.

The deuteration of the acid-soluble organic fraction in carbonaceous meteorites may result form interstellar molecules synthesized by ion-molecule reactions or grain surface reactions (as discussed in the section on Molecular Composition mentioned above). For the kerogen it is perhaps more likely that the measured deuteration results from photochemical modification processes in the interstellar medium. Although formed at high temperatures and densities in circumstellar outflows, PAHs are also likely to be highly deuterated (*Allamandola et al.,* 1987). In this case, the deuteration is due to unimolecular dissociation following UV photon absorption, which because of the small zero-point energy difference tends to favor H-loss over D-loss. It should be emphasized that only small PAH molecules (<30 C atoms) will lose hydrogen efficiently in this way (*Tielens et al.,* 1987).

In this respect, note that kerogen in meteorites is structurally very similar to amorphous carbon and most likely consists of small clusters of PAHs (e.g., soot). Figure 6 compares the laboratory Raman spectrum of activated carbon with that of meteoritic kerogen (Murchison), an interplanetary dust particle (Attila), and the IR emission features observed in Orion. All these spectra are very characteristic for an amorphous carbon structure. Note that for a very highly disordered structure the IR active and Raman active modes are very similar in number and frequency and thus this comparison is legitimate. Needless to say, although the structural similarily evidenced by this figure provides support, it does not *imply* an evolutionary link.

SUMMARY AND FUTURE DIRECTIONS

In my opinion, it is likely that magnetic fields play a dominant role in star formation process. However, many important questions still remain. Magnetic fields and their associated Alfvenic turbulence may stabilize a cloud against self-gravity and the gravitational contraction is then driven by ambipolar diffusion of the support field. Fragmentation in such an environment is not well understood, but it is likely that small (0.1 pc), dense (3×10^4 cm^{-3}) fragments will form. Such fragments can no longer be supported by Alfvenic turbulence and a period of rapid ambipolar diffusion will set in. The role of angular momentum is also unclear. Obviously, magnetic braking of the clumps as well as fragmentation can reduce the angular momentum considerably. When the former dominates, single stars with associated planetary disks may form, while double stars may result from the fragmentation process. However, by no means has the the initial mass function or the frequency of double stars been explained.

In this picture, the degree of ionization and its evolution in a molecular cloud forms an integral part of the star formation process. Although some work has already been done, important physical and chemical processes have not been taken into account. These include ionization of metals by penetration of the ambient interstellar UV field or internal UV sources, the accretion (or neutralization) of metals on dust grains, and the possible dominance of PAH anions in dense clouds. A detailed study, which combines dynamics and chemistry in a magnetically supported cloud similar to those for free falling clouds (*Tarafdar et al.*, 1985), seems in order. Obviously, direct determinations from observations carry even more weight.

Magnetic fields also seem to play an important role in the mass loss dominated phase of a protostar as evidenced by, in particular, the prominent optical jets. Again, Alfven waves may couple the ions and neutrals and drive the CO outflow as well. Alternatively, the stellar mass loss driving the observed CO outflows may be predominantly neutral and atomic. In that case, the anisotropic density distribution near the protostar then channels the outflow in two opposing lobes. The acceleration of the stellar wind occurs close to the stellar surface or in the inner parts of the circumstellar accretion disk. Rotational energy may drive the wind, possibly through magnetic energy (field reconnection), and giant coronal holes near the rotational poles may be responsible for the narrow confinement observed in the optical jets. Stability of the wind/accretion-disk system near the acceleration zone is of some concern. Some HH objects may actually result from instabilities in this region.

Finally, the observed preservation of interstellar material is one of the most exciting discoveries in the last 10 years. The actual possibility of analyzing stardust material, which still carries some of the nucleogenic and chemical memory of its birth site, will provide an important stimulant not only for studies of the protoplanetary disk but also for stellar nucleosynthesis and galactic evolution studies. In particular, their incorporation into meteorites without major modification needs to be investigated. This undoubtedly carries much information on the physical and chemical history in the interstellar medium, of the star formation process, of the processes in the protoplanetary disk, and on the meteoritic parent body. For example, it is likely that the higher densities and temperatures during the collapse phase irrevocably changes the signatures (e.g., D enrichment, ions, radicals) of ion-molecule gas phase chemistry. Accretion and reaction on grain surfaces at low temperatures may lead to large deuteration effects in icy grain mantles. However, if there is an efficient exchange between gas phase and icy grain mantle species then this may also not be preserved during the collapse phase. Nevertheless, some of the deuteration effect may be passed on to more refractory daughter products, such as the organic refractory dust component. Furthermore, before entering the accretion disk around the protosun, the interstellar material will experience an accretion shock, whose strength will depend on position. The influence of this shock on the chemical composition of the gas phase and solid dust grains is a major unsolved issue. Laboratory studies form a key part of any research project in this area. These include basic studies of the chemical processes important in the deuteration of interstellar PAHs and interstellar icy grain mantles, as well as gas phase reactions. Pyrolysis studies of grains as well as entrapment studies of noble gasses under simulated interstellar and protoplanetary disk environments are also very relevant for this problem.

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INVITED TALK

OBSERVATIONS OF STAR FORMATION

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I. INTRODUCTION

Since stars and their planetary systems form together, the study of the origins and evolution of solar systems must include the study of star formation. Evidently, the stars form out of the dusty molecular clouds in the Milky Way. In the later stages of their formation before they reach the main sequence, these young stars, e.g., the T-Tauri stars, have shed some of their obscuring cloak, and they may be studied by their emission in all parts of the spectrum. In the earlier stages, they are enveloped in dust and gas, and only the longer wavelength radiation gets out. Furthermore, at the earliest stages, when cold material is presumably collapsing to form the central star and the disk that will become the planets, the process can only be observed in its long wavelength emission. Thus it is in the far infrared and short (millimeter and submillimeter) radio wavelengths where we must look to see the earliest stages.

In this brief review and discussion of future prospects, it will be useful to keep in mind the angular scales of the various processes that we are observing at present or hope to see in the future. The nearest star-forming clouds are in Taurus at a distance of 150 pc, and this sets a minimum angular scale for direct observation of various phenomena. In the following list, these scales are given in parentheses. A stellar core, like our sun, is on the order of 10^{11} cm or 0.01 AU (10^{-4}″). The disk, in which material of higher angular momentum accumulates, is expected to have a radius in the range of a few to a few hundred AU, i.e., up to 10^{16} cm (2″) (*Terebey et al.*, 1984). If our own solar system is a general guide, planets form at radii up to 40 AU, 6×10^{14} cm (0.25″). In order for the velocity of material falling freely onto a core of about one solar mass to exceed the local gas sound speed by a factor of, say, three (and therefore be observable), it must be within a radius of about 10^{16} cm (2″). Lower speeds will be lost in the background random fluctuations. Dark dust patches in the clouds have scales on the order of one pc (130″). Finally, the giant clouds themselves have scales of typically 40 pc (1.5°).

Processes at some of these scales are observed directly, and others can only be inferred by modelling of spectra. In the later pre-main-sequence stages when the stars are observable, their atmospheres are studied with spectroscopic models. The disks, if they have persisted, may be seen with speckle techniques. In the middle infrared the typical angular resolutions of 1–2″ or worse allow only spectroscopic models of the disk and core. At the longer IR wavelengths, typical angular resolutions are poorer. With the airborne Kuiper telescope observing in the range 100–1000 μm, as with the single millimeter wavelength dishes, the angular resolutions are typically one arc minute. This is also the typical IRAS resolution. Giant molecular clouds and cores (dark patches) can be resolved at this scale, but spectral models are necessary for smaller structures. The recent development of interferometer arrays at millimeter wavelengths, which have achieved resolutions of just a few arc seconds, and the construction of large single submillimeter wave telescopes are changing the picture.

The following is a selective review of the present observational status of objects that have some bearing on star formation: giant molecular clouds, cloud cores and T-Tauri stars, outflows, infall, disks, and interstellar chemistry. Prospects for the future will be summarized in the concluding section.

II. GIANT MOLECULAR CLOUDS

Figure 1 shows an example of a giant molecular cloud taken from a survey by *Blitz and Thaddeus* (1980). What we see here are contours of peak intensity in the J = 1–0 emission from CO, a molecule that is ubiquitous in the galaxy and that can be observed in emission whenever the density exceeds about 100 hydrogen molecules per cubic centimeter so that it is adequately collisionally excited. The angular resolution here is about 10 arc minutes, and one can see the typical kind of structure, long and stringy with density concentrations on a wide range of scales. There is an an enormous amount of mass here, tens of thousands of solar masses. These are the objects from which individual stars and clusters condense.

Figure 2 (from *Fuller and Myers*, 1987) shows the CO distribution in another direction in Taurus-Auriga in a few contours. Also shown are dense cores (dark patches), obscured stars (infrared stars), and T-Tauri stars (known

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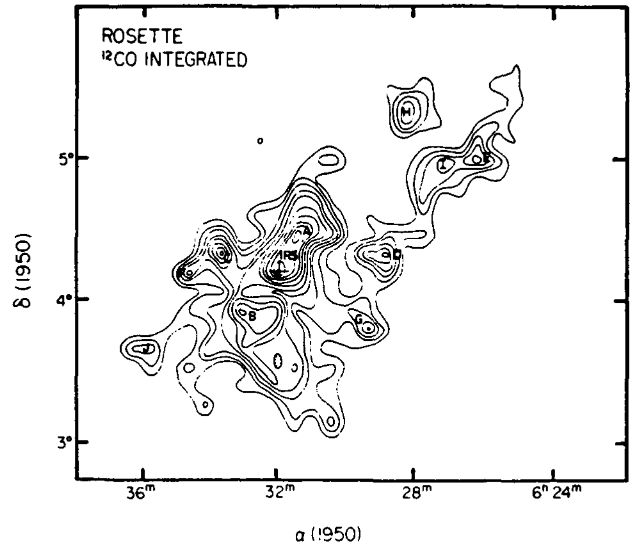

Fig. 1. Map of the integrated CO emission; contours are 1 K-MHz (*Blitz and Thaddeus*, 1980).

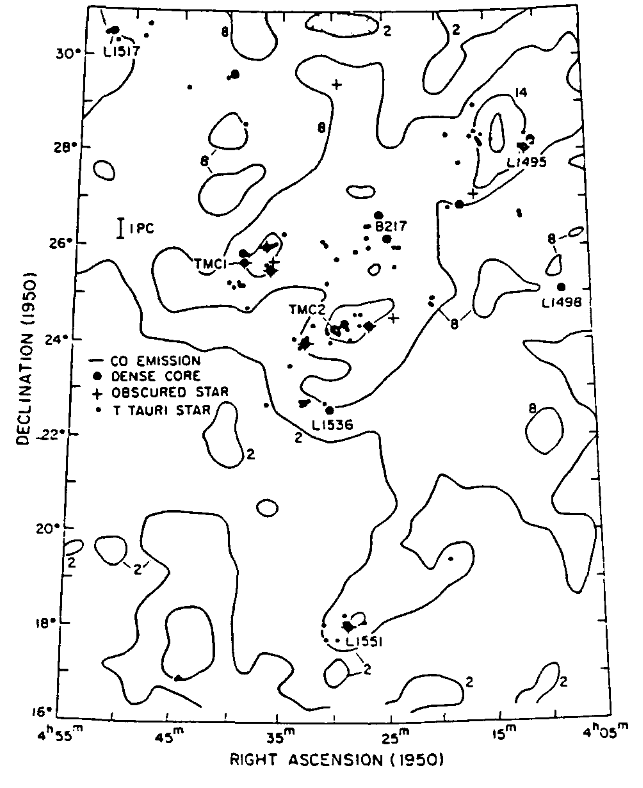

Fig. 2. The distribution of molecular gas (CO), cores, highly obscured stars, and T-Tauri stars in the Taurus-Auriga region (*Myers*, 1987).

pre-main-sequence stars). These objects cluster near one another and the CO peaks from which they presumably condensed. There may well be a temporal sequence here with the CO peaks being the first objects formed and the T Tauri stars the latest stage of evolution: CO → core → IR star → T-Tauri. About half of the cores contain obscured infrared objects.

III. CORES

The cores or dark patches (regions of high visual extinction) have higher densities than other parts of the CO cloud and may be the second stage in the formation process after a CO clump has condensed. The higher density is indicated by emission from molecules such as CS and NH_3, which require molecular hydrogen densities of 10^4–10^5 cm^{-3} to be excited into emission. Figure 3 (*Fuller and Myers*, 1987) is, on the left, a photograph of the sky from the Palomar plates, which includes the dust cloud L234A. One can see stars here and also the absence of stars, which shows largely dusty regions, regions of greater density. On the right is a map in ammonia, which is at the same scale. The molecular emission peak corresponds to the darkest region on the left. The hydrogen density is about 5×10^4 cm^{-3} and the mass about one solar mass. On the average, the cores show little rotation, have kinetic temperatures of about 10K and linewidths of 0.3 km/sec (slightly more than thermal), and have free fall lifetimes of 2×10^5 years. Cores without imbedded infrared sources have linewidths of 0.2 km/sec, as expected for gas at 10K, but cores with imbedded sources have broader lines, typically 0.4 km/sec. The greater width could be due to either gravitational infall or outflows.

IV. OUTFLOWS

Although it has been known for some time that the T-Tauri stars have winds, it was a surprise when it was

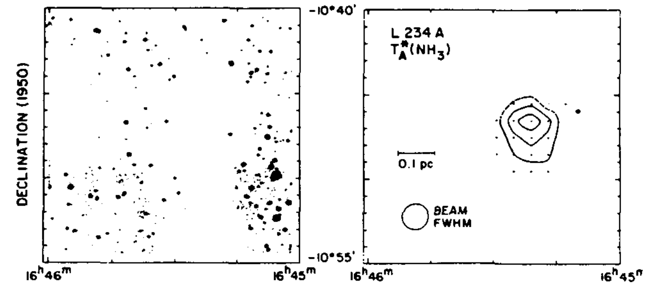

Fig. 3. On the left is the Palomar photograph of the dark cloud L 234 A. On the right is the map of peak temperature in the (1,1) line of ammonia (*Fuller and Myers*, 1987).

discovered that a large number of the imbedded IR sources have winds that are both stronger and frequently bipolar. Figure 4 shows the L1551 core of Fig. 2 in a sequence of three panels with successively higher resolution (*Lada*, 1985). In the top panel the outline of the red shifted CO gas (solid line) is clearly displaced from the outline of the blue shifted gas (dashed line) on either side of the obscured IR source, showing the bipolar flow of swept-up gas. The central panel is an optical picture of the outflow and the bottom panel shows, at the highest resolution, elongated radio continuum emission; all are aligned. Similar outflowing structures are the optically visible Herbig-Haro nebulosities (*Schwartz*, 1983) and the water vapor masers at radio wavelengths near the highest luminosity sources (*Genzel et al.*, 1981). Both show large radial velocities and proper motions indicating that they are material moving rapidly away from the central imbedded infrared source.

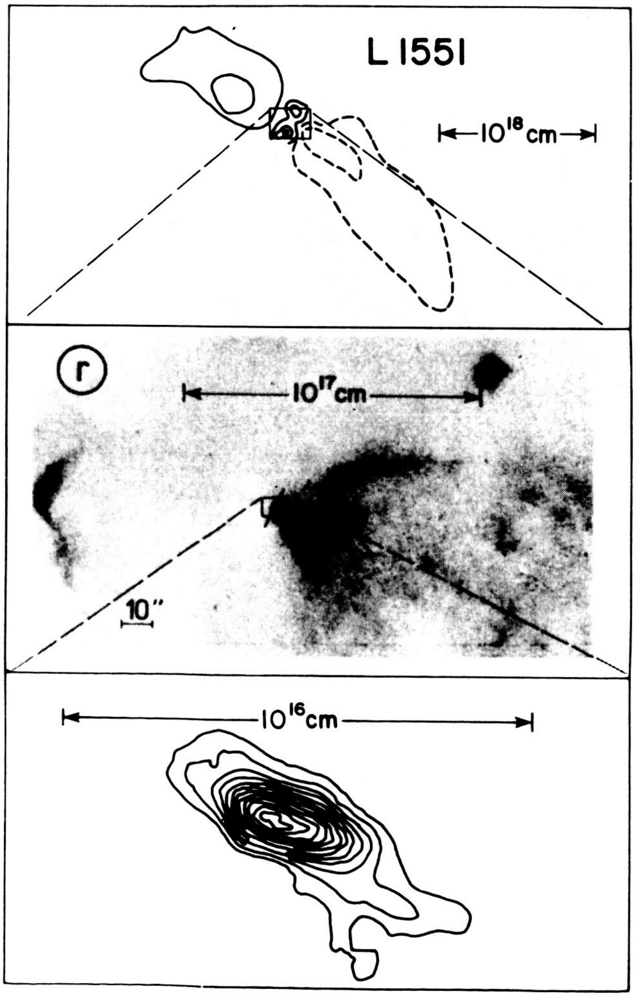

Fig. 4. Collimation of the L1551 outflow at three different scales. Top is the CO flow. Middle is an optical image. Bottom is a VLA radio (6-cm) image of the core (*Lada*, 1985).

Whereas the T-Tauri stars show winds with velocities up to 400 km/sec and mass losses of typically 10^{-7} solar masses/year, the CO outflows have lower speeds but much higher mass flows, in some cases as large as 10^{-3} solar masses/year. The winds appear to originate at or close to the surfaces of the central stars and in some cases are highly collimated optical jets. The CO flows may well be gas swept up by winds of neutral hydrogen from the stellar surfaces. The wind mechanism is not well understood. Figure 5 (*Lada*, 1985) shows measurements of the mechanical luminosities and radiant luminosities for a number of winds. There is at least a rough correlation, with the radiant luminosity always larger. On the other hand, the outflow momentum is typically quite large compared with that of the stellar radiation, indicating that direct radiation pressure is not the mechanism.

One striking effect of the winds is on the chemistry of the nearby surrounding material. On the large scale the chemical compositions of molecular clouds show fairly uniform abundances, and ion-molecule chemical schemes

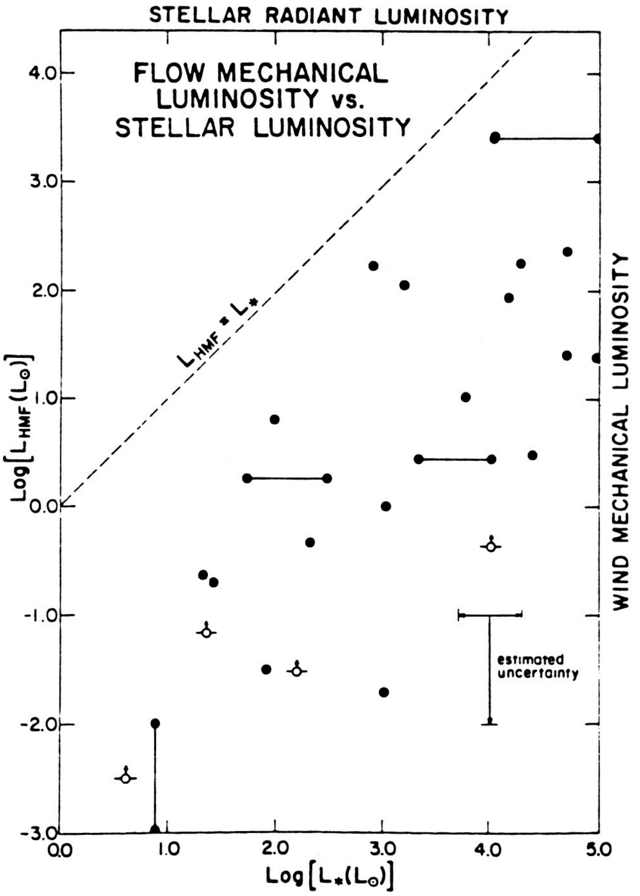

Fig. 5. Mechanical luminosity of the outflow is plotted against radiant luminosity of the central star (*Lada*, 1985).

explain the observed abundances of most species reasonably well. Near the outflows there are major chemical changes. The composition shifts from being what one would expect in a mainly carbon-rich environment in the large cloud to being sulfur- and silicon-enhanced and apparently oxygen-rich close to the outflow. Figure 6 shows Hat Creek Interferometer maps of several molecules in the Orion A outflow, all at a radial velocity of 19 km/sec (VLSR), except for the NH_3, which is the line integrated map (*Plambeck et al.*, 1983; *Vogel et al.*, 1984). The 19 km/sec is well away from the local background cloud velocity, and the map resolutions are in the range 3–8″. The differences between the distributions are considerable. The continuum emission is from dust in dense clumps surrounding the imbedded star. The ammonia lies mainly in this hot stationary material and may be the result of sublimation of grain mantles. The SO and SiO have very broad velocities and are greatly enriched, suggesting the destruction of refractory grains by the winds. The HCO^+ also has wide velocities but a greater extent, very like that of the 2 μm H_2, and may be the result of magnetohydrodynamic shocks in the outer reaches of the winds.

V. DISKS

Disks are expected to form with the stars, and there is both inferential and direct evidence for their existence. Material with high angular momentum must fall into the disk, after which some may fall onto the star, some may form planets, and some will be blown away by the winds. One piece of inferential evidence is that the winds are collimated in the optical jets into very narrow beams. The collimation might be by disks. More convincing evidence comes from the broad infrared spectra of some of the

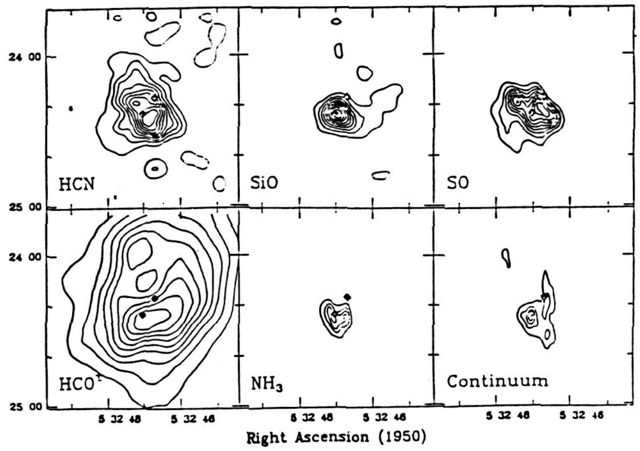

Fig. 6. Orion A maps of λ 3 mm continuum, integrated ammonia, and other millimeter lines from Hat Creek at 19 km/sec (*Plambeck et al.*, 1983; *Vogel et al.*, 1984).

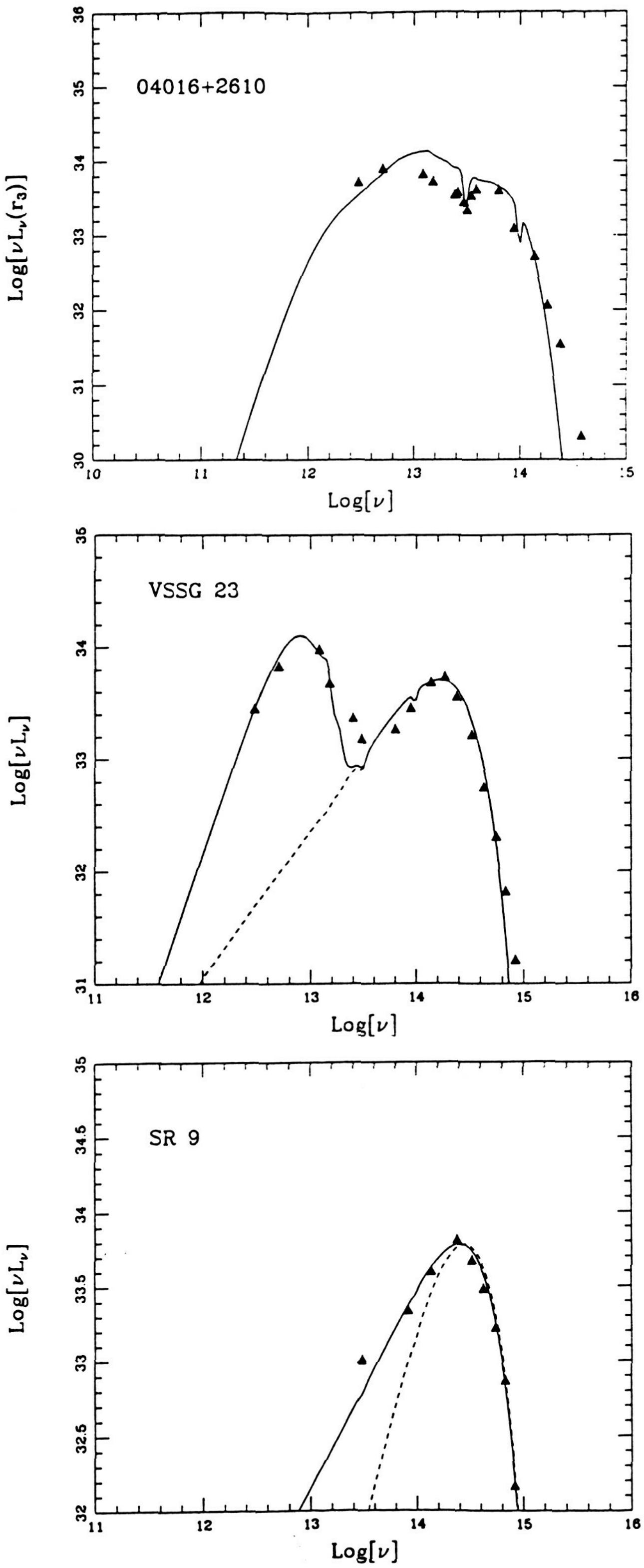

Fig. 7. Spectra of pre-main-sequence objects. Solid lines are theoretical spectra allowing for infall onto both a stellar core and a disk (*Adams et al.*, 1987).

imbedded sources. These exhibit strong far infrared emission from circumstellar dust. However, if the dust were spread uniformly about the star, the short wavelength extinction would be much greater than what is observed. The dust must have a nonspherical distribution, and the obvious candidate is a disk. In Fig. 7 (from *Adams et al.*, 1987) the spectrum of 04016+2610 is fit very well by an accreting protostar in which a disk is forming. The spectrum of VSSG 23 is fit by a model of an imbedded T-Tauri star onto which infall has nearly stopped, and the model for SR 9 is a revealed T-Tauri star with an optically thick disk and no infall.

There is more direct evidence of a disk in the interferometer maps of *Sargent and Beckwith* (1987) of the star HL Tau. Figure 8 shows their map of the distribution of the integrated emission from ^{13}CO, an elongated disk-like structure about 4000 AU in extent. There is about 0.1 $M_\odot$ of material here at a mean temperature of a few tens of Kelvin. The resolution of 6″ is barely able to resolve the disk. However, the positional centroids of the individual velocity channel maps can be determined more accurately, and they show the interesting distribution of Fig. 9. This distribution indicates Keplerian motion and that the gas is bound to the 1 $M_\odot$ star. The reality of this disk in this recent study seems firm. Although this is a unique result, coupling it with the inferred disks above suggests that indeed the formation of disks with stars is common.

VI. INFALL

It was noted above that angular resolutions of 2″ or better would be required to resolve the expected infall of gas in the early stages of the formation of a star like our sun. The spectroscopic signature of this has been sought in low-resolution single-dish studies but has proven to be illusive. The probable reason is the background "noise" of random motions and especially the persistent outflows that mask the small velocities of the infall. Yet this is an important and expected part of the star formation process.

Recently, infall has been detected but on a rather different scale than the collapse onto a single star. *Welch et al.* (1987) have reported evidence for the collapse of the massive core of the star-forming region W49. Figure 10 is a VLA image of the 6-cm emission from the HII regions in the cloud core. The ring-like collection of HII regions near the center exhibits a velocity gradient along its major axis consistent with rotation, with an implied contained mass of 5×10^4 $M_\odot$. Figure 11 shows a spectrum of HCO$^+$ (1–0) (λ 3.4 mm) toward the brightest HII region in the ring taken from a 6″ map made with the Hat Creek Millimeter Interferometer. At this angular resolution the continuum brightness of the ionized gas is high enough

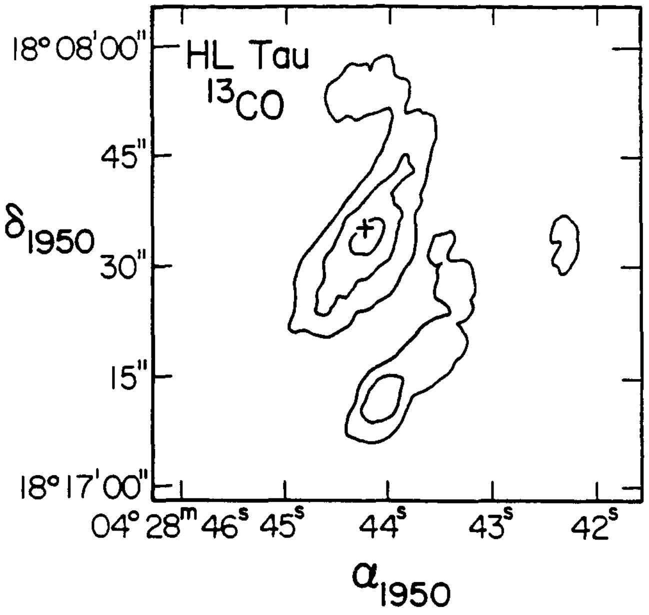

Fig. 8. Map of the integrated ^{13}CO emission from the disk around HL Tau from Owens Valley (*Sargent and Beckwith*, 1987).

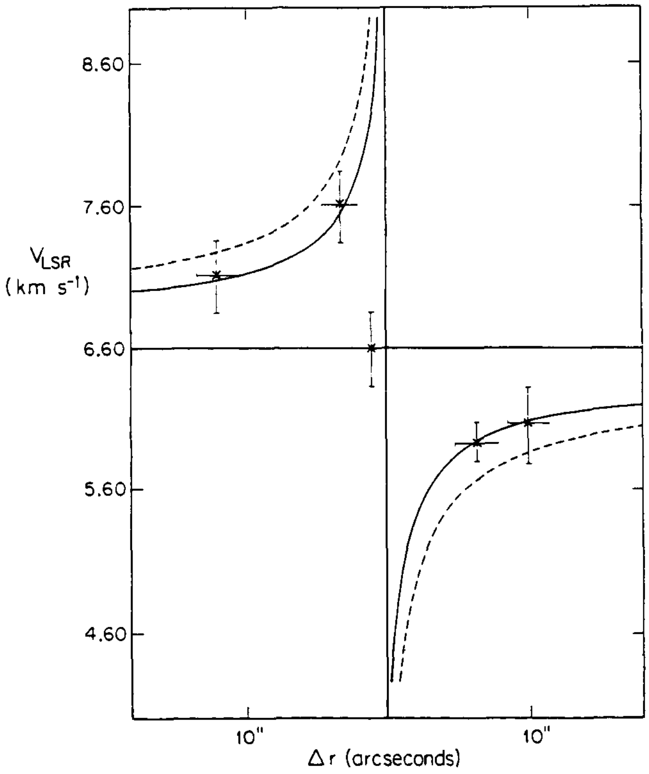

Fig. 9. Distribution of radial velocity of the ^{13}CO around HL Tau at different distances. The lines are theoretical curves based on Keplerian rotation (*Sargent and Beckwith*, 1987).

Fig. 10. VLA λ 6-cm image of the core of W49, showing emission from the many compact HII regions (*Welch et al.*, 1987).

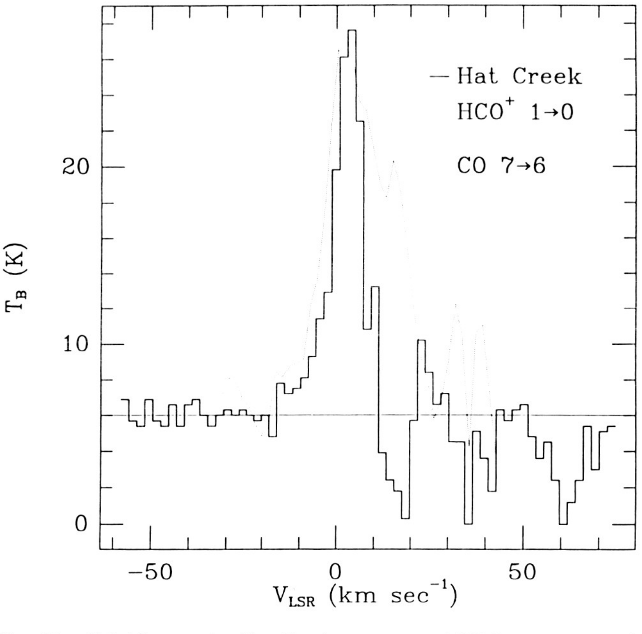

Fig. 11. Solid line is the Hat Creek spectrum of HCO$^+$ (1–0) toward the brightest compact HII region in the ring in the W49 core. Dashed line is the CO (7–6) emission from the core.

to reveal an important absorption by the HCO$^+$ just in front of the ring. Red shifted gas over 10–20 km/sec shows in absorption, whereas blue shifted gas is in emission. That the blue shifted gas must be behind the continuum source and the red shifted gas in front implies that the gas is falling into the ring from all sides. Furthermore, the observed absorption spectrum corresponds nicely with free fall onto a mass of 5×10^4 $M_\odot$, which is at a mean velocity of 8 km/sec. The dotted spectrum is emission from highly excited CO. It fills in the absorption quite well, as we would expect, since the near foreground collapsing gas will not contain such highly excited CO.

Here is strong evidence for infall, but it is the collapse of a large core to form a cluster of O stars and not the collapse onto a single star. It is, in fact, the large central mass with its concomitant large infall velocity that has made the observation possible. In any case, infall is real. If this is interpreted as an inside-out collapse, a large sound speed is implied for the gas. In turn, this suggests that strong magnetic fields are playing a major dynamic role here. They provide a large sound speed in the form of Alfven waves, which allow the large-scale coherent collapse, and they resist the initial collapse of the cloud in one direction until a large mass has accumulated. Indeed, large fields have been detected in the core of this cloud through observations of the Zeeeman splitting of the OH line (*Gaume and Mutel*, 1987). It may be that the strength of the field decides whether large or small mass stars form.

VII. SUMMARY AND FUTURE PROSPECTS

Progress in understanding star formation is proceeding rapidly on the observational side. Much has been learned about the physical and chemical properties of the molecular clouds. Remarkably intense winds from imbedded young stellar objects have been discovered. There is now clear evidence for disks and for infall at the early stages. Magnetic fields seem to play an important role, at least for the formation of massive stars in clusters. Many questions remain. Does the wind stop the accretion? Perhaps the star decides how much mass it is going to have by turning on the winds and blowing away the material that would otherwise fall on it. On the other hand, there is evidence that the winds are coeval with the infall, and they may be dynamically related. What are the roles of the disks? Presumably they allow accretion of the higher angular momentum material. They may collimate the winds. They are the birthplaces of the planets. How is the final mass of a star determined? What determines the sizes, masses, and radial distances of the planets?

What does the future hold? The ability to make radio wavelength images at about 6″, rather than about 60″, with interferometers has enabled the direct detection of disks and infall. To focus on the details of disk formation and to measure the infall onto single stars like our sun will require angular resolutions on the order of 0.5″–1.0″ or better. To study planet formation directly will require a resolution of the order of 0.1″. Some interferometric observing has already been carried out at resolutions of 1–2″ with the currently operating millimeter interferometers. During the next two to three years, these instruments plan to extend operation from λ 3 mm to λ 1 mm. Because the strength of signals from thermal sources increases rapidly with frequency and because the existing baselines will be longer in wavelengths at λ 1 mm, resolutions of 0.5″ will be possible. This means that much more work on direct imaging of disks and infalls will be possible, which should have direct bearing on questions of planet formation. Later, with longer baselines, 0.1″ will be possible, permitting direct imaging of the early stages of planet formation. Note that this work is done not only in observations of continuum emission but also at very high spectral resolution in line emission. Thus, even when the direct spatial resolution is marginal, the spectral information allows modelling of the kinematics. In summary, we can expect many more exciting results from these instruments in the next few years.

But remember that 0.1″ is still 15 AU at the distance of the nearest star-forming region in Taurus. We eventually want to get to 1 AU, and that means 0.01″. Only the planned VLA-sized millimeter array of the NRAO can approach that resolution from the ground, and the possible construction of this instrument is probably many years away. How do we proceed? It's only a matter of money. What we do is to build an infrared interferometer in space that works at 100 microns and that will do very well.

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COMPARISONS OF SOLAR NEBULA MODELS

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Our concepts of the solar nebula remind me of the fable of the group of blind men who examined an elephant. Each formed a very different impression as to the nature of the beast, depending on which part he touched—trunk, tusk, ear, side, tail, etc. I offer here my own idiosyncratic comments, and leave it to you to decide what part of its anatomy I have grasped. If I criticize anyone else's view, it is not because I claim to have superior vision; we are all groping in the dark.

Since this meeting is about the relationship between meteorites and the solar nebula, we may hope that one can tell us something about the other. Anyone who expects that is certainly an optimist. Suppose, for example, that some property of a meteorite uniquely determined the temperature and pressure at which it formed. I would be very surprised if there is any solar nebula model that could not match those conditions *somewhere* within it. Before such information becomes a constraint, we must understand an object's dynamical history: Did it necessarily form in the central plane of the disk, or could it reflect conditions far from the plane? Did it form in the asteroid belt, or was it placed there in long-term storage after forming elsewhere?

The diversity of asteroid compositions (and meteorite types) suggests that there was significant spatial and/or temporal variation of conditions encountered by the material that was left there by the time the nebula had dissipated. A more modest constraint on the nebula, with lower resolution, may be found in the general trend of planetary compositions with heliocentric distance. If one assumes that this is due to some degree of chemical reaction between solids and gases (exact equilibrium is not necessary), the resulting compositions are rather insensitive to pressure, but might at least constrain the temperature profile.

This has been taken to heart by a lot of people, perhaps a bit too much. Figure 1 is *Lewis'* (1974) picture. Based on the composition of various objects in the solar system he argued that the original solar nebula had a rather steep temperature gradient—something like R^{-1}, steeper than the radiative equilibrium solution. Since he did this, a number of other proposals have come about for explaining the composition of Mercury (point 1 on this figure) and these models have nothing to do with the temperature at that location. The two outer points (6 and 7) refer to the compositions of the satellites of Jupiter and Saturn, respectively, and they may refer to conditions in circumplanetary nebulae rather than the solar nebula. So the correlation is a bit tenuous if you take away these points; a radiative profile cannot be ruled out. Also, there is no guarantee that this represents a "snapshot" of the nebula's temperature at any one instant of time. Nonetheless, you will see that these diagrams reappear several times in the course of my talk. It seems to be somewhat of a Holy Grail for solar nebula modelers. Now to accompany that temperature profile, I'll give you another piece of the elephant, which is a reconstruction of the surface density you would get if you took the present masses of the planets and reconstituted them with their solar-composition complement of H and He (Fig. 2; *Weidenschilling*, 1977). Whether or not this has anything to do with the solar nebula depends on your assumptions with regard to the mechanisms of planet formation and whether that process was uniformly efficient with distance from the sun. However, if you do this exercise you find

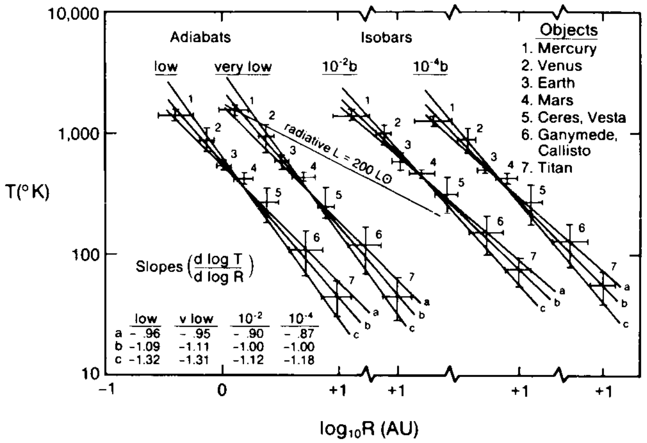

Fig. 1. Temperature gradient in the solar nebula inferred from planetary compositions (*Lewis*, 1974).

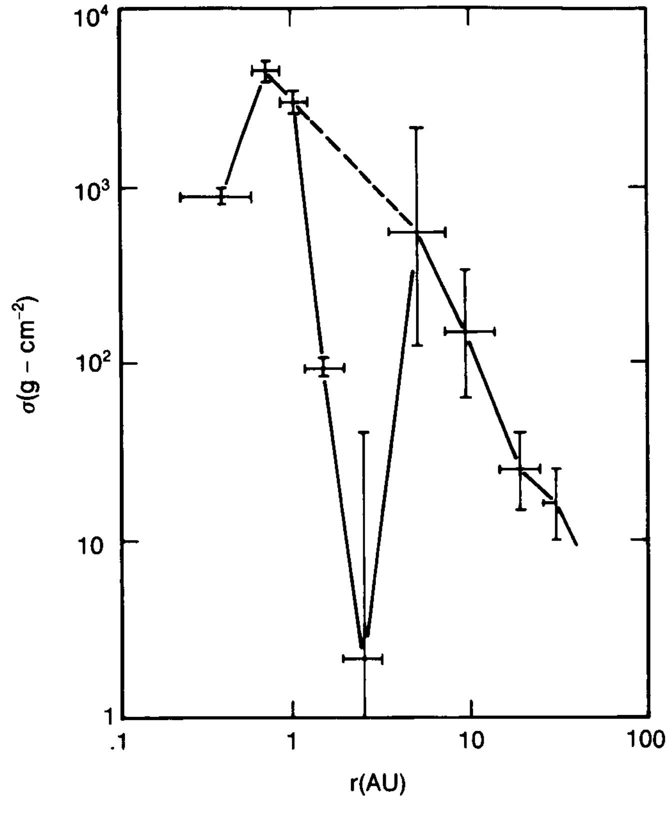

Fig. 2. Surface density in the solar nebula inferred from the reconstituted solar-composition masses of the planets (*Weidenschilling,* 1977).

a fairly steep gradient of surface density that is approximately $R^{-3/2}$. The published solar nebula models do not meet that gradient particularly well, at least not the ones that propose to explain the formation and evolution of the solar nebula.

I am going to talk mostly about turbulent models of the solar nebula, for the simple reason that nonturbulent models have no predictive capability. Anything that goes on in them has either happened earlier when it formed in the first place (which may have been a turbulent stage), or happens later during the accretion of bodies into larger bodies, which John Wood will talk about next. You are free to choose any surface density or temperature (as in the two previous figures). Nonturbulent nebulas just serve as a reservoir of raw material and a place for things to happen if, for instance, you are interested in the dynamics of accretion.

To relate solar nebula models to the previous talks we can talk about the collapse of a rotating protostellar cloud. *Cassen et al.* (1985) use simple dimensional arguments to point out that if we start with a certain amount of mass, M, and angular momentum, J, there is a natural scale to which the cloud would collapse, a centrifugal radius, R_c. The actual value will depend on what you assume for the density distribution within the cloud, whether or not you have uniform rotation before the collapse. An order of magnitude scaling argument gives $R_c \sim J^2/GM^3$. Once it collapses to a disk, it undergoes differential rotation and shear. If there is some sort of viscosity, ν, in this system, then you will have evolution whereby the disk spreads out. Some of the mass will flow inward, which is fine if you want to make the sun; there must also be some outward motion to absorb the angular momentum that is being transferred. There is a "viscous radius," $R_v \sim (\nu t)^{1/2}$, where ν is the kinematic viscosity and t the evolutionary time. We might separate the disk evolution into two stages: first a collapse to a centrifugal radius, and then, if the viscosity is high enough, further spreading of the disk as time goes on. Cassen et al. suggest that the size of the system should be based on whichever of these two expressions is larger. The characteristic diffusion time, or spreading time for this viscous disk, is simply the square of a characteristic length divided by the effective viscosity, whatever that might be.

Cassen et al. also show by dimensional arguments that if the viscous disk evolves for a long time so that $R_v >> R_c$, the ratio of masses in material that has moved outward and absorbed the angular momentum (the disk) and the material that has moved inward and lost angular momentum (the star) is of the order of $(R_c/R_v)^2$. Since the centrifugal radius is fixed by the initial conditions, and $R_v \propto t^{1/2}$, the disk/star mass ratio eventually varies inversely with time. The energy dissipation that takes place during this evolution gives an effective temperature. The dissipation rate is proportional to the central mass times the rate at which mass is flowing inward due to loss of angular momentum; it is just the rate at which gravitational potential energy is being released. If we assume that it is converted into heat locally and radiated away, we have an effective photospheric temperature at which this object radiates

$$T_e \sim \left[\frac{GM_{\odot}\dot{M}}{\sigma_s r^3}\right]^{1/4} \qquad (1)$$

Depending on the optical thickness, the actual temperature for the bulk of the mass can be considerably higher. As a crude estimate, we take 10^{52} g cm^2/sec of angular momentum, which is a bit more than we can currently account for in the solar system of planets augmented by lost hydrogen and helium. If the central mass is one sun, the effective centrifugal radius is about 100 solar radii, or about 1/2 AU. If we allow this to evolve viscously for a long time, out to a viscous radius of the present size of the solar system, the disk mass is of the order of a tenth of a solar mass, which is the canonical solar nebula mass. To do that on the timescale for the cloud collapse, $\sim 10^5$

years, you would need an effective viscosity of the order of 10^{17} cm^2/sec, a rather high value. Dynamically it seems to work, but chemically this would be a disaster in the sense that all of the matter taking part in this evolution would be heated to a temperature of the order of 2000 K. There would be no preserved isotopic anomalies, and no preserved low temperature material from interstellar space from before the collapse. That does not necessarily rule out models of this type, but certainly the extreme end member does not work. If you wish to have any preserved low temperature material with this kind of model, you need a late veneer of infalling low temperature material landing on the disk after it had grown to something approaching its present size.

An alternative is to assume a larger mean angular momentum so that the centrifugal radius is about the size of the present solar system. That requires an order of magnitude more angular momentum. After the collapse to the centrifugal radius, most of the material that has to form the sun has to move inward from there. Most of the published models of the turbulent accretion disk solar nebula are based on the implicit assumption that the material in the disk is moving inward toward the center. Then the mean temperature of whatever you want to have left over to form the planets increases with time during the process. You still require a very large viscosity to do this and the source of that viscosity is rather uncertain.

The turbulence in these models is driven by convective instability, which is sort of a perpetual motion machine. If convection starts in the disk, this leads to a turbulent viscosity that is rather high. The differential rotation or shear in the disk then causes considerable energy dissipation, which causes heating that drives the convection. The energy source for all this is the motion of the disk material inward in the gravity well of the central star. Something that is required to make this work, however, is that the disk is optically thick so that the energy is convected within the disk rather than radiated. The gas opacity is very small, so solid grains must provide most of the opacity. The assumption of the models is that the gas and grains are well mixed, and that the size distribution of the grains can be ignored. This means that the sizes of all the grains are very small with respect to the dominant wavelengths at which radiative transport would occur. In that case, the opacity is a function of temperature only. If the grains are small enough, then the opacity goes as the square of the temperature and has to increase more rapidly than about the square root of the temperature in order for the model to be convectively unstable.

These models are known as "alpha models," and that does not tell us a whole lot. There is a great deal of argument in the literature over what is the proper value of α to use, but it is simply a fudge factor. We express the turbulent viscosity in this form

$$\nu_t \equiv K\alpha VL \tag{2}$$

(some arbitrary coefficient, K) times (some arbitrary velocity, V) times (some arbitrary length, L) times (the fudge factor α). Everyone uses a different set of values for those. Some people use a coefficient of 1/3 or 2/3 or 1 for K. The velocity may either be the local eddy velocity or the sound velocity, and the length may be a physical thickness of the disk or a pressure scale height or the largest eddy size. I have converted the various models in the literature to the same notation, expressing all in terms of the sound velocity, c, and a characteristic length, which is c divided by the local Kepler frequency, Ω. Assuming that the gamma of the gas is 1.4, we define the effective viscosities that come out of these models, $\nu \equiv \alpha C^2/\Omega$. In this uniform notation, *Cameron's* (1985) assumed values of α range from 0.13 to 0.31. *Morfill's* (1985) model, which nominally appears to assume a different value of α due to different definitions of the other quantities, turns out to be identical to Cameron's lower value, 0.13. *Lin and Papaloizou* (1985) estimate α from mixing-length theory, and use a value lower by about a factor of 20 from Morfill's value. More recently, *Cabot et al.* (1987), using Canuto's theory of convective instability, derive much lower convective velocities. They compute the turbulent viscosity directly, yielding values that correspond to a much lower effective α in the range of 10^{-3} to 10^{-4}. The really fundamental property is not α, but the actual values of the viscosity and the eddy velocities. In the models of Cameron and Morfill, the convective velocity is assumed to be about 1/3 of the local sound speed. Lin's mixing-length model derives convective velocities that vary through the thickness of the disk, but average out to about a tenth of the local sound speed. Cabot et al., using a different theory, derive velocities that vary with height and radius in the disk, but average about one percent of the local sound speed.

There are two ways to go about constructing these models. One is to assume a steady state—which is to simply choose a rate of mass inflow, $\dot{M}$, across any given radius, or a timescale on which you want to form a body of 1 solar mass, then assume or compute the convective velocity, α, and the effective viscosity. Once you do that, then knowing M and the viscosity, one computes the local surface density from the relation

$$\Sigma(r) = \dot{M}/2\pi\nu(r) \tag{3}$$

The value of Σ is set by the other assumptions. Since viscosity may actually depend on the temperature, which depends on the convective velocity and on Σ, you have to adjust the parameters a bit to get things to come out consistently. Steady state models are used to compute a local surface density profile. If you started out with something that was not steady state, with the mass inflow rate varying with radius in the disk, it would adjust itself to something approaching uniform $\dot{M}$ in regions where the viscosity varies. Higher viscosity will simply decrease the local surface density, and lower values of ν allow mass to pile up, increasing Σ, so that the mass inflow will stay about the same.

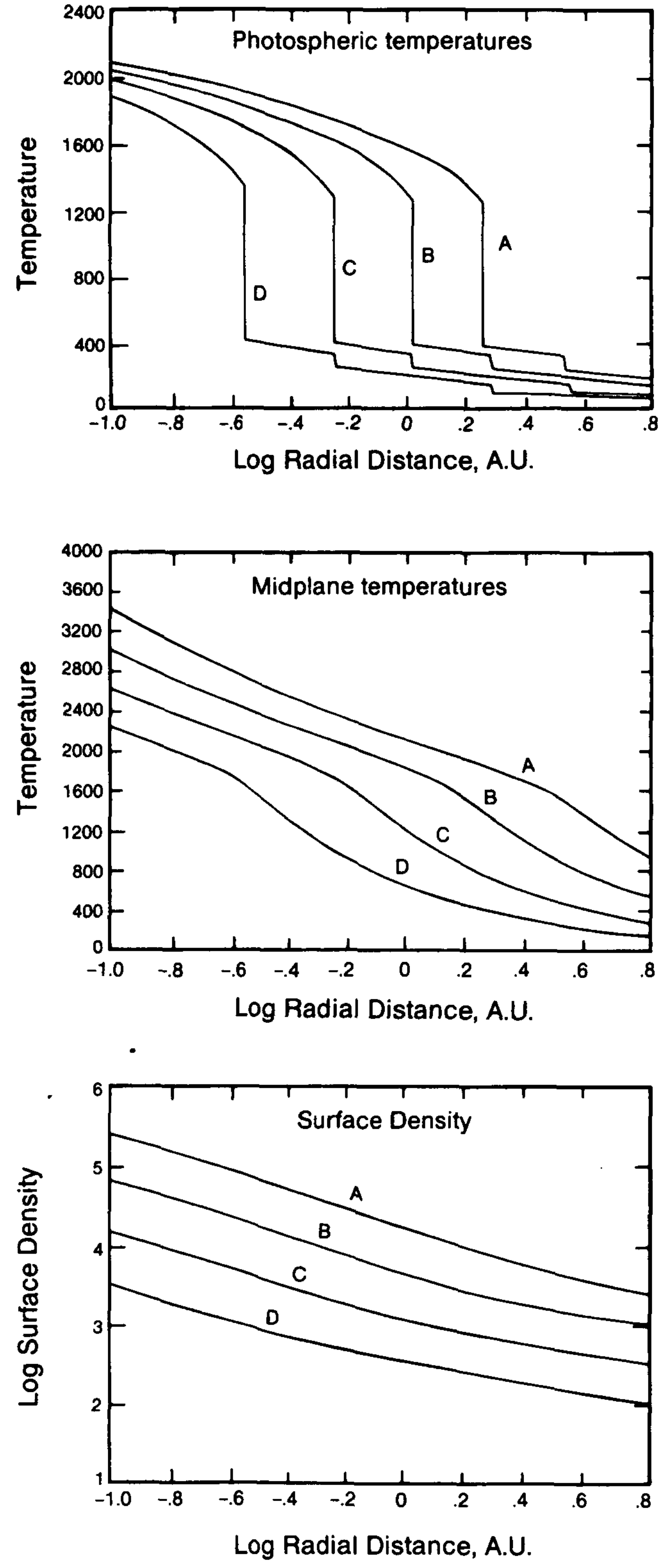

Fig. 3. Photospheric and midplane temperatures and surface densities for the inner parts of turbulent disk models of *Cameron* (1985). The different models assume different infall rates, with values decreasing from A to D.

Figure 3 is from *Cameron* (1985). It shows parameters for disks with different infall timescales or mass inflow rates. The turbulent viscosity is about 10^{17} cm^2/sec—a perfectly typical value for the inner part of the disk, what one needs to get evolution times of the order of 10^5 years. The evolution times that Cameron defines are slightly different from the viscous evolution times; it is the time to get 1 solar mass processed through a disk of this sort. The disks themselves are much less than a solar mass, but the matter is moving through them more rapidly and any given element of mass will pass on through the disk and be absorbed into the forming sun fairly quickly. His point there was that the rate at which this happens depends on the surface density of the disk and increases with Σ, so the disk adjusts itself to the local infall rate. As matter falls in more quickly, the disk raises its surface density until the flow of mass from the disk into the forming sun matches the infall rate onto the disk. For these models Cameron gets rather high midplane temperatures—at 1 AU it's a couple of thousand Kelvin. There is no attempt to match the temperature profile to planetary compositions. These models are at the upper end of assumptions for the viscosity. This is being optimistic about the magnitude of the convective velocities, the parameter α (for what that's worth), and the effective size of the eddies. These are about the highest conceivable values of viscosity and the shortest evolution times.

Morfill et al.'s (1985) models are perhaps also somewhat allegorical. They have been primarily interested in solving the chemistry of the solar system based on turbulent diffusion of condensates that appear at different temperatures. In order to produce a reasonably tractable analytic solution for relative abundances, they made explicit assumptions in their model: The surface density and viscosity are taken as constants throughout the disk. From equations (1) and (3), that constrains the photospheric temperature to go as $R^{-3/4}$. The temperature gradient is steeper in the central plane; Morfill et al. assume a gradient of $R^{-3/2}$. Thus, this should not be taken literally for predicting the compositions of various solar system bodies

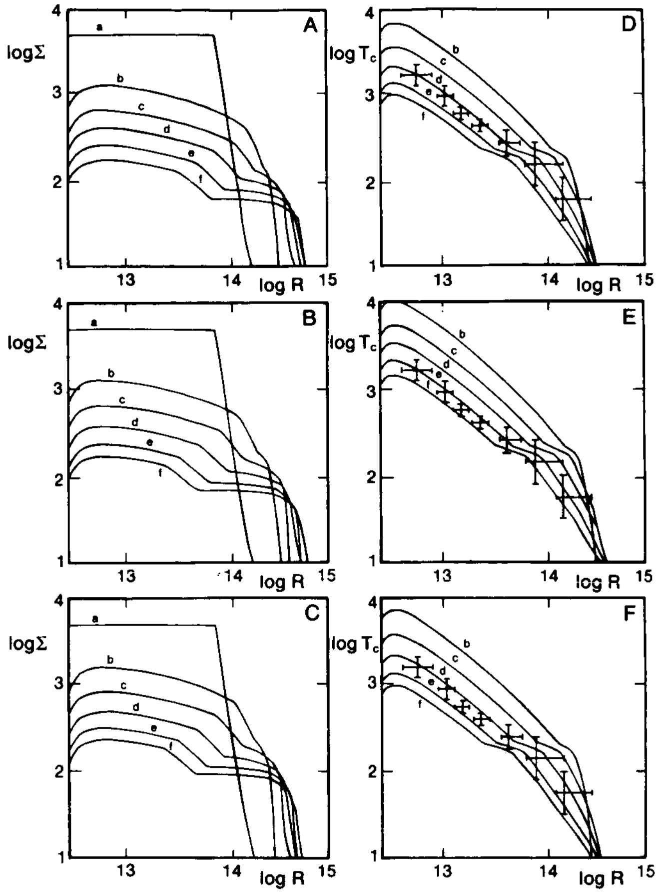

Fig. 4. Time evolution of surface density and midplane temperature for disk models of *Lin and Papaloizou* (1985). The models use different values of α, decreasing by a factor of two between cases.

in terms of the local temperature in the disk. Morfill et al. get a slightly longer viscous evolution time than Cameron does (by a factor of 2) for similar disk parameters, because their assumed viscosity is down by a factor of 2.

Lin and Papaloizou's (1985) evolutionary models start with an initially uniform surface density profile. Although they use mixing-length theory to estimate convective velocities and turbulent viscosity, α is assumed to be constant throughout the disk. They allow the surface density to evolve with time. Most of the mass is moving inward across the inner boundary, and therefore the surface density decreases in the inner part of the disk. The outer regions, which are soaking up the angular momentum, expand with time. Lin and Papaloizou also match the Lewis temperature profile in this way (Fig. 4). The evolution times are about an order of magnitude greater than for Morfill's model, because their viscosities (or α) are lower.

Cabot et al. (1987) get yet another result. Their disk surface density profile is shown in Fig. 5. The peaks in the local surface density appear because the local opacity at the various evaporation/condensation boundaries affects the computed viscosity. They apply that literally with respect to its effect on the structure of the disk. Actually, this sawtooth profile will be softened by radial mixing due to the eddies. In spite of their extremely different assumptions, they also end up matching the Lewis temperature profile rather well. This suggests that the temperature gradient is a necessary condition, but not sufficient to tell you what the solar nebula was like. Temperature is a very poor constraint on the nebula, because it only varies as the fourth root of most of its properties. Cassen et al. made the point that no matter

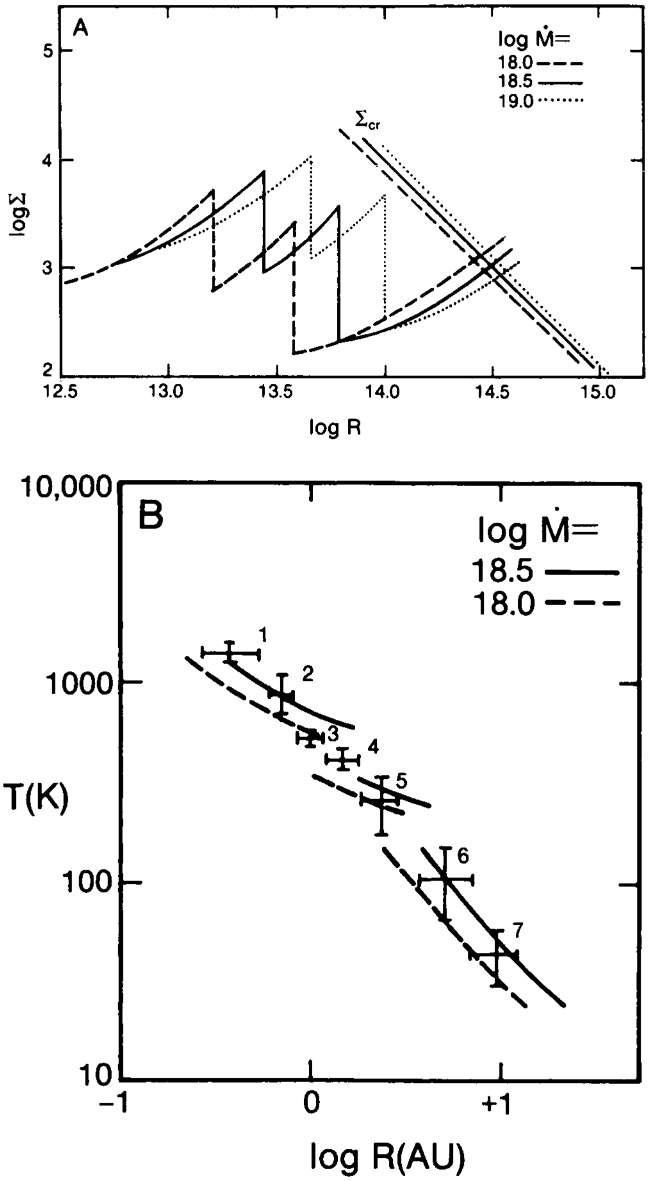

Fig. 5. Steady-state surface density and temperature distributions for disk models of *Cabot et al.* (1987) for different values of the rate of mass inflow.

how you model such a disk, the photospheric temperature profile approaches an $R^{-3/4}$ law, which is not very different from the Lewis temperature gradient.

I mentioned the opacity of the nebula as driving convection, and the size distribution of the grains being an important factor therein. *Pollack et al.* (1986) have computed opacities for solar composition grain mixtures with different sizes. Not only does coagulation decrease the actual opacity as the mean grain size increases, but its temperature dependence decreases as well. As I mentioned before, if the opacity varies more slowly than the square root of the temperature, convective instability does not occur. That has not been taken into account in any of these solar nebula models at this point. A few years ago I did a schematic sort of calculation (*Weidenschilling,* 1984) of the evolution of opacity in a disk based on Lin's model. Turbulent convection brings grains together and causes them to coagulate. What happens in this model (Fig. 6) is that, as grains coagulate due to their relative motion due to turbulence, the opacity drops because they form aggregates that are large compared to the relevant wavelengths. Radiative transfer gets more efficient. At some point as the aggregates get larger they are able to cross the smaller turbulent eddies and acquire larger relative velocities. If they collide with each other and have only a finite strength, they will break each other up. After some oscillations, this calculation ended up at a steady state in which large aggregates were destroyed as quickly as they were created. Depending on what sort of feedback one would assume between the local opacity and local convective velocity, one could have either a steady state solution or a steady decline in the turbulent velocity due to a clearing of the nebula. This is an area that needs to be investigated further, because none of the convective disk models explicitly take into account evolution of the grain opacity due to coagulation. They generally assume that during this time you will be able to form large bodies, i.e., planetesimals, while the nebula is convecting, but it would seem that one would need to lower the convective velocities below some critical threshold in order to get coagulation to occur and large bodies to grow.

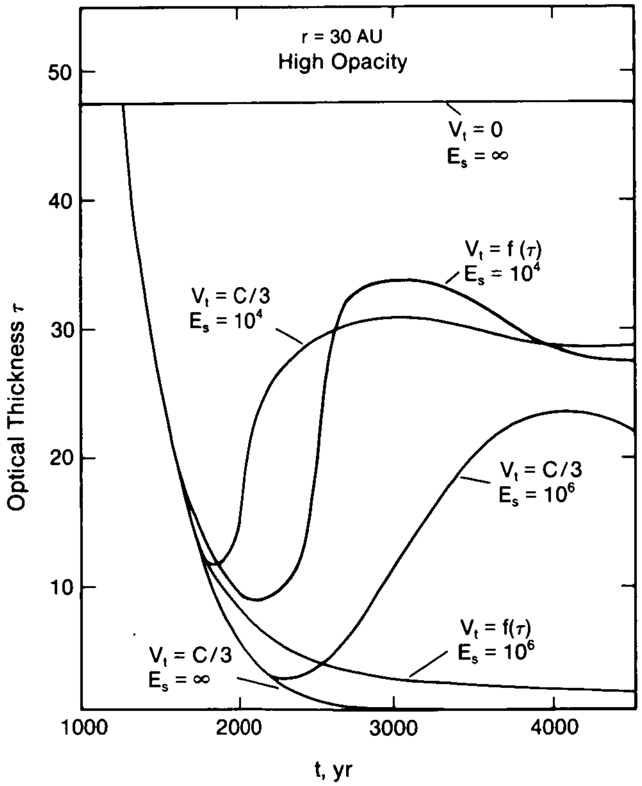

Fig. 6. Time evolution of optical thickness due to grain coagulation in a turbulent disk (*Weidenschilling,* 1984). The various cases assume different values for impact strength of grain aggregates, and turbulent velocities either constant at one third the sound speed, or proportional to the optical thickness of the disk.

Lin and his co-workers have also considered tidal interactions between a large protoplanet in the disk and the gas of the disk itself. The gravitational effect of the protoplanet on the surrounding gases is such as to transfer angular momentum and push the gas away from the orbit of the protoplanet. Lin and Papaloizou maintain that the giant planets would not grow to their present sizes by collecting gas from the nebula unless the gas is sufficiently turbulent that the viscosity can overcome this tidal torque. That, however, assumes that one has a reasonable understanding of the interaction between a protoplanet and a gaseous disk. I think that the theory is not very convincing yet, as it neglects or greatly simplifies effects of finite disk thickness, pressure gradients in the gas, etc. Whether or not that's a real constraint on the degree of turbulence in the nebula remains to be seen.

I would like to summarize some questions that occurred to me in preparing this talk. Infall onto the disk is an alternative source for producing turbulence, due to material falling onto the surface of the disk with mismatched angular momentum. This also produces heating at the top of any layer of the disk and would tend to produce a subadiatic gradient that would suppress convection. It's not clear which effect wins (if either one). We need to know something more about the theory of turbulent convection to decide between models that are very different. Despite their differences, both Lin et al. and Cabot et al. claim to have theoretical support for their models and offer explanations (by very different mechanisms) for the FU Orionis phenomenon of outbursts observed for some PMS stars. At this point I think that it's too early to judge if either of these models is correct.

There needs to be more investigation of the role of grains in the evolution of the opacity of such a disk. What are the minimum values of opacity and optical thickness required to sustain convection? The role of tidal torques in the formation of the giant planets needs further study to determine whether or not that is a real constraint on the structure of the nebula.

Here are some observations and experiments that I would like to see that might answer some of these questions:

1. Could we actually observe convection in a protostellar disk and resolve that from infall/outflow, rotation, etc.?
2. It would be good if we could measure a dust/gas ratio in some protostellar disks to find out if there is evidence for the coagulation or settling of the dust and resulting opacity changes.
3. We need some theoretical treatment of convection that is believable and supported by experiments (where feasible) and numerical simulations.
4. Experimental work is needed on the collisional behavior of grains to determine with parameters that can be used in coagulation models.
5. Finally, we need to spend an amount of computer time and effort on the evolution of the disks themselves as we are spending on the collapse of the prestellar clouds. I include in this category both viscous evolution and tidal interactions with protoplanets. That should be amenable to someone who has a 3-D hydro code and can model the evolution of these disk models in a more realistic fashion.

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INVITED TALK

PHYSICAL PROCESSES AND TIMESCALES IN PLANET AND SMALL-BODY ACCRETION

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A series of processes in the solar nebula transformed infallen interstellar grains into planets. Somewhat surprisingly, samples of planetary material from the very first stages of this processing and aggregation have been preserved, and are accessible to us for study in terrestrial laboratories. These are the chondritic meteorites, which have passed the last 4.5 Gyr safely stored in asteroids, bodies that are too small to have become internally hot and thus geologically active. My discussion will follow the outline in Table 1, most of which is Meteoriticists' Conventional Wisdom regarding the processes that occurred in the solar nebula. The nebula is taken to have been a viscous accretion disk similar to the nebula models developed by astrophysicists in the last decade (*Wood and Morfill*, 1988).

1. Chondrites are aggregations of three principal components: abundant *chondrules*, millimeter-sized spheroids of igneous silicate material, which apparently were formed by the remelting of earlier forms of dispersed matter; less abundant *refractory inclusions*, also formed at high temperatures, but whose compositions were strongly influenced by selective evaporation and recondensation of elements (i.e., distillation); and *matrix*, fine (order of a micron) mineral grains now packed between the larger components, which probably formed by condensation of hot vapors into dispersed dust particles.

Current nebula models do not predict high gas temperatures (i.e., $T \gtrsim 400$ K) at the radial distance where asteroids would have formed. Some nebular process beyond the vision of modellists pervasively heated and processed interstellar grains prior to the beginning of aggregation; the fraction of material in chondrites that can be construed to be unprocessed interstellar material is extremely small.

There is reason to believe that this thermal processing was not produced by sustained high temperatures in the nebula, but resulted from discrete energetic episodes, localized in time and space. Part of the evidence lies in the time scales of thermal processing of the chondrules and refractory inclusions, which have been established. The rate at which a molten droplet cools controls the textural pattern of crystals that form, and also the degree of chemical zonation that is preserved in the crystals. Droplets of appropriate composition have been cooled in the laboratory under carefully controlled conditions, and furnace products that cooled in minutes or hours were found to have textures and zonations comparable to those observed in natural chondrules and inclusions (*Hewins*, 1983, 1988). Also, molten droplets would be unstable against evaporation in the nebula, and experiments have shown that after the order of an hour they would have vaporized totally (*Hashimoto*, 1983). Such a rapid time scale dictates that the heating events were small and transient. If a large part of the nebula had been hot enough (1500–2000K) to cause the observed thermal effects, it could not have been cooled

TABLE 1. Outline of putative planet-forming processes in the solar nebula.

Process	Timescale	Dimension of product
1. Thermal processing of interstellar grains into chondrules and refractory inclusions; in discrete episodes, in dust-rich zones of the nebula	minutes, hours	microns-mm's
2. Sticky agglomeration of chondrules, refractory inclusions into clumps	$\lesssim$100 yr.	> 10 cm
3. Settling to midplane of the nebula	~10 yr.	> 10 cm
4. Stage 1 of Goldreich-Ward instability	~1 yr.	~100 m
5. Stage 2 of Goldreich-Ward instability	~10^4 yr.	~10 km
6. Gravitational accretion of planetesimals into planets	10^7-10^8 yr.	~1000 km

on a time scale this short, nor could particles embedded in it be moved to a significantly cooler environment so rapidly.

Table 1 stipulates "dust-rich zones" because there is evidence that many chondrules and refractory inclusions were thermally processed in chemical environments of noncosmic (nonsolar) composition: In particular, the O/H ratio in the surrounding gas was greater than cosmic. This ratio controls the redox potential of the gas, and the redox potential controls the oxidation state (the content of Fe^2) of chondritic minerals that crystallize in equilibrium with it. Most chondrules and some refractory inclusions contain minerals that would have been at equilibrium with a gas much more oxidizing than the cosmic mixture (*Rubin et al.*, 1988). The only obvious way to achieve this state in the nebula is to postulate solid/gas fractionations prior to thermal processing episodes. When the heating occurred, vaporization of part of the dust in a dust-rich zone would enhance O/H in the gas, since the dust consists largely of oxides. Unvaporized solids (perhaps only the larger grains or aggregates) would then find themselves in an O-rich gas (*Wood*, 1967). It is more likely that solids would physically fractionate from gas in a system like the nebula than that the latter could have remained well-mixed.

2. Table 1 has the dispersed chondrite components beginning to aggregate, after their thermal processing, in a rather short time—less than a century (and I think it may have been much sooner than that). However, there is not widespread agreement on this point. Several lines of evidence point to prompt accretion (*Wood*, 1985, 1987). Chondrite subtypes can display major differences in texture and mineralogy, even though their bulk chemical compositions are almost identical. For example, Fig. 1 compares the textures of a CV3 and a CO_3 chondrite. The textural difference must reflect minor variations, temporal or spatial, in the way nebular processing was producing chondrules. Presumably each subtype represents a discrete processing episode, bounded in time and/or space. If the dispersed chondrules had continued to orbit for thousands of years before they aggregated, these morphological populations would have become mixed and the textural identities of the chondrite subtypes would have been lost. Accretion must at least have begun soon after chondrule formation. "Less than a century" is a rather arbitrary time scale to name, but the dispersed chondrules could not have circulated in the nebula for very many orbital periods without becoming mixed with solids that had been thermally processed at substantially different radial distances.

Additional evidence comes from the Murchison C2 chondrite. Although Fe/Si (molar) in the chondrules and refractory inclusions of Murchison (~0.20) and in the matrix (1.23) are distinctly different from the solar ratio (0.90), Fe/Si for bulk Murchison (0.81) is nearly solar. There is a complimentarity in the compositions and proportions of chondrules/refractory inclusions and matrix: Apparently Fe that was evaporated from the chondrules and refractory inclusions by the heating event that processed them recondensed and joined the matrix dust, after which chondrules, refractory inclusions, and dust accreted almost quantitatively. This had to happen promptly, to forestall aerodynamic fractionation of the dust from the larger components. (Murchison is one of the few chondrites where it is possible to observe this effect. Most other C2s are more affected by planetary hydrothermal alteration, which would have caused postaccretional Fe exchange; the chondrules of C3 and UOC chondrites have intrinsically higher Fe contents—their Fe does not seem to have been as extensively evaporated during the chondrule-forming event.)

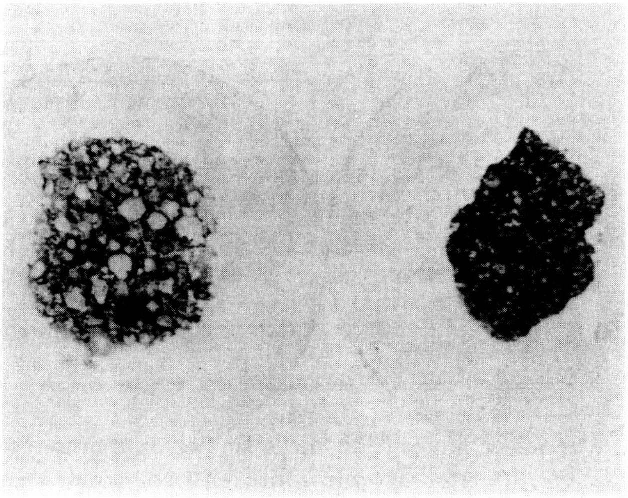

Fig. 1. Thin sections of two carbonaceous chondrites, illustrating differences in aggregational textures of chondrites that have almost the same bulk chemical compositions. Glass disks on which sections are mounted are ~1 inch in diameter. Left: Vigarano, a CV3 chondrite. Right: Warrenton, a CO3 chondrite. Figure from *Wood* (1985).

Finally, chondrules in UOC chondrites appear to have begun to aggregate with matrix dust while some of the chondrules were still hot and plastic, judging from the way they indent and mold around one another (Fig. 2; *Holmen and Wood*, 1986). This would require that accretion at least began very promptly, indeed as a continuation of the chondrule-forming thermal event (i.e., on a time scale of hours or less, as noted earlier).

Table 1 specifies that masses of diameter >10 cm aggregate in the nebula; this is because smaller aggregates could not settle toward the nebular midplane (the next in the canonical stages of planet formation) through a turbulent gas (*Weidenschilling*, 1987). *Weidenschilling* (1984) notes

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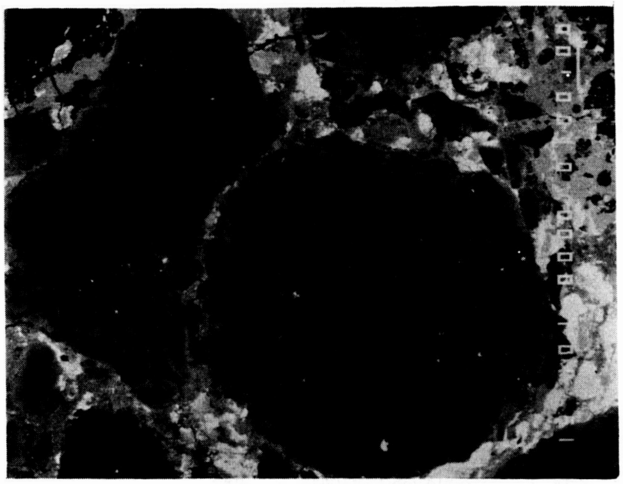

Fig. 2. Chondrules in the Krymka LL3 chondrite that appear to have indented one another by coming together while one was still plastic. Width of field, 1.1 mm. SEM back-scattered electron image, courtesy of B. A. Holmen.

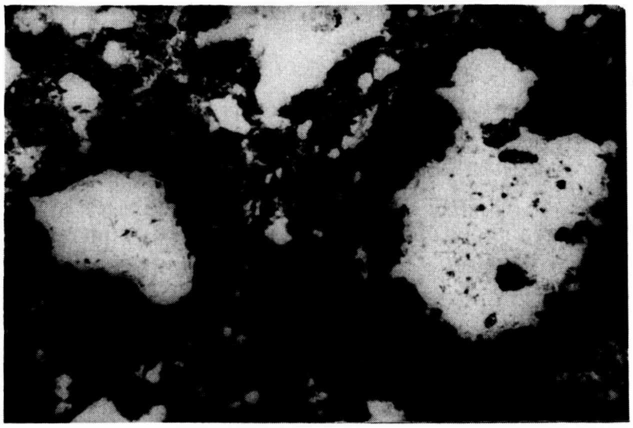

Fig. 3. Thin section of the Pollen C2 chondrite, showing two chondrules (light) surrounded by dark rims or haloes of accreted fine-grained material. Width of field, 1.2 mm.

that dust would quickly coagulate into aggregations as large as ~1 cm in a turbulent gas, but could not grow beyond this because collisions between larger aggregations would tend to disrupt them. He concludes that settling (of the limiting ~1 cm aggregates) to the midplane could occur only during probably rare periods of quiescence (lack of turbulence) of the nebular gas. However, Weidenschilling assumes loose aggregates of dust, presumably held together only by weak van der Waals forces. It is possible that some stronger force held the aggregating particles together and allowed them to achieve dimensions greater than 1 cm, in which case they could settle to the midplane even through a turbulent gas.

Refractory inclusions and chondrules in thin sections of primitive chondrites sometimes display dense, dark rims or haloes (Fig. 3); fine-grained material, similar but not identical to the matrix that fills in between chondrules and refractory inclusions generally, has formed a coating on the chondrules before they aggregated into bulk chondritic material. *Bunch and Chang* (1980) found these haloes to be enriched in carbon (approximately twice the concentration in matrix generally). Most of the carbon in these haloes and matrices consists of complex, macromolecular material of grain size <500 A that must have formed by nonequilibrium processes in the nebula and the interstellar medium. This material is insoluble in solvents and most acids, and relatively refractory. It is not unlike terrestrial asphalt, and may have served to strongly "glue" accreting chondritic particles together (a suggestion first made by *F. Hoyle*, e.g., 1955). The word "sticky" in Table 1 alludes to such a bonding agent.

3. Settling to the midplane has already been discussed. The time scale shown, ~10 yr., is from *Weidenschilling* (1980) and follows from the force balance on a 10-cm object between gravity and drag.

4. Discussions of the onset of planetary accretion invariably assume that it was brought about by gravitational instability of a thin zone of solid particles densely concentrated near the nebula midplane. A dust layer embedded in the nebula can be gravitationally unstable even though the overall nebula is gravitationally stable. The problem has been treated by *Goldreich and Ward* (1973), who recognize two stages in the formation of planetesimals from smaller objects (such as the 10-cm settling aggregations discussed above).

The first stage consists of direct gravitational collapse of small objects that are relatively close to one another. These form a generation of planetesimals of radius ~100 m and density ~3 g/cm^3. This happens rapidly, within about a year after the dust layer becomes thick and dense enough to become unstable.

5. The resulting disk of ~100-m planetesimals is still gravitationally unstable, and its members tend to draw together into clusters mutually orbiting the sun, each containing ~10^4 planetesimals. On a time scale of a few thousand years dissipative forces (especially gas drag) tend to reduce the differences in orbital velocities of cluster members. The clusters contract and merge into second-generation planetesimals, of radius ~5 km.

Goldreich-Ward accretion has been accepted uncritically by meteoriticists, perhaps out of relief at having the thorny problem solved of how planets could be gotten started in their accretion (i.e., how can there be net growth of planetesimals that are too small to have appreciable gravitational fields?). It is in a category of stock concepts along with regoliths, the T-Tauri solar wind, 10^{-3} atmospheres, the cosmic abundance of the elements, and "the nebula was then dissipated." In fact, certain conditions have to be met for the process to operate, and it has not been established that they were met.

Factors that work against G-W accretion are (1) random motions of the objects trying to accrete, such as would be imparted to small particles by gas turbulence or by gravitational perturbations by larger planetesimals once these had begun to form, and (2) relative motions caused by the different orbital parameters of objects (i.e., differences in their angular momenta) if the size of the source volume of objects (and therefore the final mass of the accreted planetesimal) is not small enough. These disturbing motions have to be small enough to be overcome by the mutual gravitational attraction of bodies in the source volume.

It is not clear that gas turbulence would not prevent the operation of G-W Stage 1 accretion. Even if there was no thermally driven convective turbulence at the stage when accretion began, shear caused by differences in rotation rates of the dust layer and the gas above and below it would generate turbulence in the boundary zones (*Weidenschilling*, 1980. A pressure gradient in the gas nebula helps support mass elements of it at their radial distances, so rotation of the nebula is at somewhat less than the Keplerian velocity. Solid objects near the midplane orbit at their full Keplerian velocities, and the density of them is so great that they drive the gas, too, at the Keplerian velocity.)

It is also not clear that gravitational disturbances would not keep random motions of objects pumped up to velocities too high to permit G-W Stage 2 accretion to operate. It might seem that planetesimals could not grow large enough to gravitationally perturb unless Stage 2 accretion *had* operated, but in fact an orbiting cluster of small objects exerts gravitational force outside the cluster equivalent to that of the planetesimal expected to accrete from it. This might make the process self-defeating. The passage of clusters near to one another in their orbits could keep their members too stirred up to allow them to draw together.

The alternative, if G-W accretion didn't do the job, is that accreting material was actively sticky enough and inelastic enough that planetesimals could continue to grow (there were cratering losses, of course, but on average some planetesimals at least grew in size) until they became large enough ($\gtrsim$1 km) to have appreciable gravitational fields, after which accretion becomes easier to understand.

6. Beyond about a kilometer dimension, the motions and aggregation of planetesimals are controlled by gravity. The effects of gas (and whether, in fact, it is present or absent at this stage of accretion) are of almost no consequence. The final stage of planetary growth is a well-defined problem in dynamics and material properties, with an extensive literature (e.g., *Safronov*, 1969; *Wetherill*, 1980; *Safronov and Vityazev*, 1985).

RECOMMENDATIONS

Workshop speakers were asked to identify areas in which additional research might bring important new insights. I suggest the following.

1. We need to understand the nature of the astrophysical events or processes that thermally alter dispersed silicate (etc.) matter to form chondrules, refractory inclusions, and matrix dust. Meteoriticists have been blunting their spears on this problem for decades. I feel strongly that a major obstacle to progress is the fact that the problem lies partly in astrophysics and partly in Earth sciences, and these two communities have great difficulty in communicating. A conscious effort needs to be made to overcome this barrier.
2. How did the particulate components of chondrites begin to stick together? I think the answer lies in the organic constituents of (even the noncarbonaceous subtypes of) chondrites. We need more detailed studies of the rims/haloes on chondrules and refractory inclusions, especially by organic chemistry and light-isotope groups. Laboratory simulations of organic synthesis under conditions analogous to those in the nebula will also be important.
3. The question of Goldreich-Ward gravitational instability should be reopened, and considered in more detail than it has been.
4. Sections of primitive chondrites, especially large slab surfaces, should be studied carefully for textural evidence of the accretion process. Did the 0.5-m (e.g.) volume of chondritic material exposed in a slab accrete by a steady particle-by-particle rain; did it come together all at once; or did it accumulate hierarchically (small grains came together into somewhat larger aggregates, these aggregates accumulated into larger masses, etc.)?

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INVITED TALK

NEBULAR PROCESSES RECORDED IN CHONDRITIC METEORITES

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The key fact concerning the chondritic meteorites is that they consist of grains that were present in the solar nebula. The most primitive (least altered) of them have preserved in their chemical compositions and in their structures evidence concerning processes that occurred in the nebula 4.5 Ga ago. We can only accept as valid those models of the formation and evolution of the nebula that are consistent with these data. Many aspects of the interpretation of the evidence are still in dispute among cosmochemists but, whatever our disagreements, those rocks were really there, their grains were really suspended in the nebular gas, and they were interacting to a greater or lesser degree with that gas. Some chondrite grains also preserve a presolar record in their isotopic compositions. It is my opinion that this presolar record has been emphasized too much in recent years. Most of what we see in the chondritic meteorites was imprinted on them in the solar nebula, and the solar nebula is the most remote evolutionary stage that we can hope to understand in a moderately comprehensive fashion.

After accretion some chondrites were thermally metamorphosed or affected by hydrothermal processes, and in these cases the nebular record is veiled by high-temperature alterations. Those chondrites that have not been metamorphosed, however, preserve much information about the earliest history of the nebula and are worthy of intense, long-term study. By studying them we can attempt to infer the times and places at which the various chondrite groups formed and the conditions present at each of these places.

Chondrites have solar interelement ratios of most elements, but there are important differences from group to group. The search for and discovery of these differences has comprised one of the most exciting areas of chondrite research. To illustrate these intergroup variations, cosmochemists plot sets of elements on abundance-ratio diagrams. Abundances are calculated by dividing the concentration of an element by that of a reference element, generally Si or Mg. The trends are then simplified by taking out primodial interelement variations in abundance; the abundances are divided by those in a reference set of materials, generally those in the volatile-rich CI chondrites that most nearly approximate solar abundances. In the abundance ratio diagrams in this paper the elements are ordered in terms of increasing volatility or decreasing nebula condensation temperatures to the right.

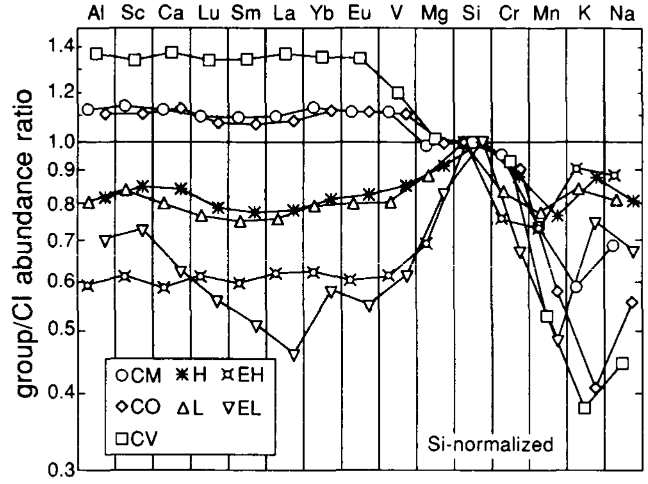

Fig. 1. Silicon-normalized group/CI abundance ratios for lithophile elements in the chondrite groups. The elements are arranged from left to right in order of increasing volatility. CI chondrites plot on a horizontal line at unity. The LL group is not plotted because it is unresolvable from the L group and available data are of lower precision. All groups except EL have a flat refractory lithophile element pattern, implying that these elements were in the same nebular component (from *Wasson and Kallemeyn*, 1988).

Interelement fractionations for the lithophiles elements, those that bond to O, are plotted in Fig. 1. The eight elements on the left (e.g., Al, Sc, Ca) form refractory oxides that are stable solids at high nebular temperatures; they are designated refractory lithophiles. There is no significant variation in the abundance ratios of the eight refractory oxides from Al to Eu, and the CO and CM carbonaceous chondrites are not resolvable. In most cases uncertainties are smaller than the size of the symbol. Mean abundance ratios range from ~1.4 in CV to about 0.6 in EH chondrites, a range of a factor of 2.3. A key question is: How can we account for this large variation in refractory elements?

A simple nebular model used by cosmochemists is: (1) the mean composition at all locations was originally solar; (2) the condensable elements were distributed in a variety of solid phases prior to accretion; (3) portions of one or more phases that are similarly fractionated, presumably by physical mechanisms, are designated components; (4) chondrites formed by the agglomeration of these components; (5) the components were not usually agglomerated in their solar proportions, thus the products are generally fractionated relative to solar (=CI composition).

Agglomeration probably resulted from the gravitational collapse of clouds of particles in the dusty midplane of the nebula. Fractionations occurred because some components were mainly present as fine particles that were suspended in the nebular gas at the time dust collapse produced planetesimals. According to this picture, refractory lithophile abundance ratios >1 reflect the suspension of an appreciable fraction of common-element (Si, Mg) components at the time of the dust collapse, whereas abundance ratios <1 reflect the suspension of dust enriched in refractory lithophiles.

Kallemeyn and Wasson (1986) recently discovered the only exception to flat refractory lithophile patterns; the pattern is fractionated in the EL chondrites (Fig. 1). It seems likely that this fractionation occurred as a result of grain-grain segregation in the inner portion of the nebula where some cosmochemists infer that the EL chondrites formed. Perhaps a drag-type inward spiraling of particles toward the sun is responsible (*Weidenschilling*, 1982). On the other hand, if such processes took place in a large fraction of the nebula over a long period of time, many similar fractionation effects traceable to small differences in partitioning among nebular phases should be present. If these exist, they are not easily recognizable. I suspect there was relatively little transport of solids relative to the gas at most locations.

For the more volatile lithophiles (Cr, Mn, K, Na) shown in Fig. 1, abundance ratios in all the chondrite groups are <1. Carbonaceous, ordinary, and enstatite chondrites have roughly similar abundance ratios of these moderately volatile lithophile elements.

Siderophile (metal-forming elements) abundance ratios are shown in Fig. 2. The common siderophiles, Fe, Co and Ni, are slightly higher in CI than in the other three carbonaceous chondrite groups. Abundance ratios of elements more volatile than Fe tend to decrease with increasing volatility. Because Fe is one of the major elements, it is especially important to understand the processes that led to its fractionation in the solar nebula. The high Fe abundance in the planet Mercury (an enhancement of the Fe/Si ratio by a factor of roughly five compared to chondritic meteorites) may be the result of nebular processes occurring near the sun.

Figure 3 is a Urey-Craig diagram. The fraction of Fe present as metal or sulfide is plotted against that bound

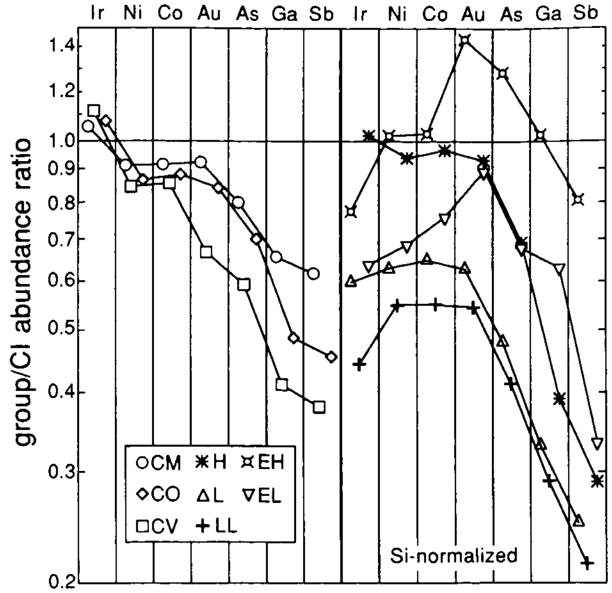

Fig. 2. Silicon-normalized group/CI abundance ratios for siderophile elements in the chondrite groups. The carbonaceous chondrites are plotted on the left half of the diagram and the ordinary and enstatite chondrites on the right half. The elements in each half are arranged in order of increasing volatility. The carbonaceous chondrites have simple patterns in which the abundance ratios decrease with increasing volatility. The patterns are more diverse for the ordinary and enstatite chondrites; a notable feature is the high Au abundance ratio in EH (from *Wasson and Kallemeyn*, 1987).

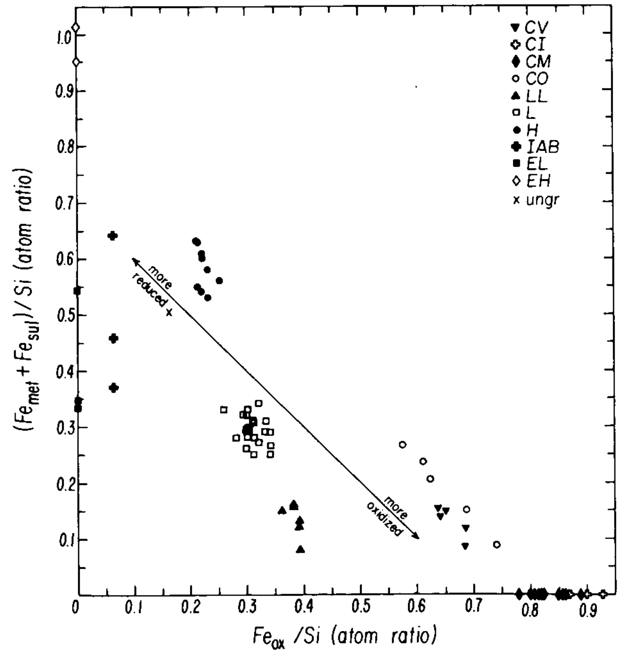

Fig. 3. On a Urey-Craig diagram "reduced" Fe (metallic Fe and Fe bound to S) is plotted against oxidized Fe (Fe bound to O). Diagonal lines of slope -1 correspond to constant Fe/Si ratios. Only the CV and CO groups form arrays with -1 slopes. The slopes in the ordinary chondrite groups (H, L, LL) are steeper and consistent with a continuous fractionation sequence connecting the three groups (from *Larimer and Wasson*, 1987).

TABLE 1. The classification of chondrites and a listing of some key taxonomic parameters.

Group	Al/Si	Mg/Si	Ni/Si	Zn/Si	$\frac{FeO_x}{FeO_x+MgO}$ (mol %)	$\delta^{17}O$ (%)	$\delta^{18}O$ (%)	Chondrule Radius (mm)	Chondrule Frac. (%)
CV	1.34	1.00	0.85	0.25	35	–3	1	0.5	50[†]
CO	1.07	0.97	0.87	0.21	33	–4	0	0.2	61
CM	1.10	0.97	0.92	0.48	43[*]	1	7	0.2	2
CI	≡1.00	≡1.00	≡1.00	≡1.00	45[*]	9	17	–	<1
H	0.80	0.89	0.94	0.092	17	3.0	4.2	0.47	80
L	0.78	0.84	0.64	0.088	22	3.5	4.6	0.46	80
LL	0.75	0.84	0.53	0.080	27	3.8	4.9	0.33	80
EH	0.58	0.68	1.04	0.49	0.05[*]	2.9	5.7	0.5	20
EL	0.67	0.81	0.69	0.030	0.05	2.9	5.7	0.5	–[‡]

[*] Estimated $FeO_x/(FeO_x+MgO)$ for equilibrium assemblage.

[†] 50% chondrules in oxidized CV, 62% in reduced CV chondrites.

[‡] Metamorphism has obliterated the record of chondrule frequency.

to oxygen. Constant total Fe is given by a diagonal line. Some highly reduced chondrites, the enstatite chondrites, plot vertically along the left axis. Some that are highly oxidized, the CM and CI carbonaceous chondrites, plot along the base of the diagram. Two fundamental kinds of Fe fractionation are shown on this diagram: (1) the variation in the bulk Fe/Si ratio by a factor of two among the chondrites; and (2) the large variation in Fe_{ox}. Iron is the only major element that can exist in more than one oxidation state in the chondrites. The other major elements, O, Mg, and (with minor exceptions) Si are always found in the same oxidation state in all chondrites.

The ordinary chondrite groups (H, L, LL) fall along a curving trend in Fig. 3. It seems likely that ordinary chondrites with intermediate properties formed in the nebula and exist as asteroids in the asteroid belt. The observed compositional gaps reflect the fact that, for stochastic reasons, the Earth is not currently sampling the entire spectrum of compositions.

Nine groups of chondrites and the chondrite inclusions from IAB irons are included in the Urey-Craig diagram. Other properties of these groups are summarized in Table 1. Already mentioned are the differences in the abundances of refractory lithophiles. Zinc is a volatile that shows distinct intergroup variations that make Zn abundance a useful taxonomic parameter. The oxygen isotope fractionations are discussed below. The processes that produced the observed variations in chondrule size and frequency are not properly understood. Mean chondrule radii range from close to about 0.5 mm down to 0.2 mm, and the fraction of chondritic matter that was converted to chondrules varies from 0% to 80%. One possibility is that, nearer the sun, there was more energy available to make chondrules and therefore a larger fraction of nebular materials was converted to chondrules.

We see evidence for nebular components in various ways. Chondrule analyses are shown in Fig. 4; a plot of Sc/Cr against FeO/(FeO + MgO) yields a negative trend. We interpret this trend in terms of the mixing of two components. One component was enriched in refractory lithophiles and highly reduced, as expected of materials formed at high nebular temperatures. At high temperatures virtually all Fe is present as metal. In a solar mixture of H_2 and H_2O, Fe oxidizes to +2 at temperatures below 1000 K and to +3 at temperatures below about 400 K. The second chondrule component was relatively low in refractory lithophiles and was oxidized, indicating formation at low temperatures. The main point is that these and other components were present within the solar nebula. We need to precisely define such components and model them using theoretical calculations of the sort Larimer and Fegley generate.

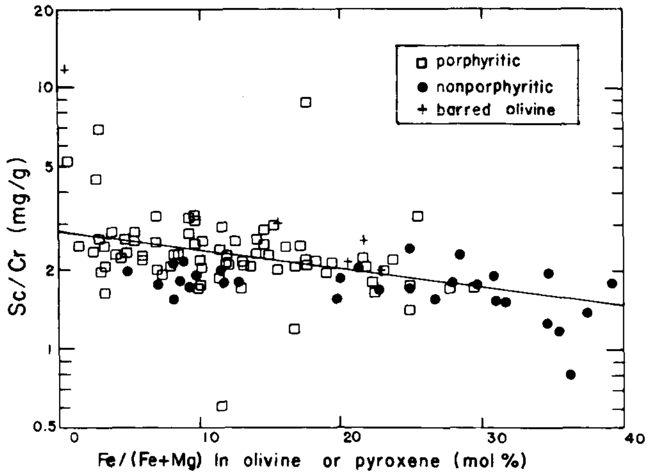

Fig. 4. In ordinary chondrite chondrules the ratio of the refractory element Sc to the common or moderately volatile element Cr decreases with increasing degree of oxidation of the mafic minerals. This trend seems best explained by the formation of chondrules from two distinct nebular components, one reduced, refractory-lithophile-rich and one oxidized, refractory-lithophile-poor (from *Grossman and Wasson*, 1983).

Chondrules can be divided into various textural categories shown by different symbols in Fig. 4. Interestingly, the relationship between chemistry and texture is not particularly strong. This is understandable if the textures mainly reflect minor differences in the temperature histories of the chondrules. For example, a porphyritic chondrule is one that has relatively large mineral grains. A nonporphyritic chondrule may be glassy or so fine-grained that the minerals cannot be resolved. If during chondrule formation the entire precursor material melted and then was quenched quickly, large crystals were not able to form. If the precursor grains did not entirely melt, the residual grains can serve as nuclei around which crystallization occurred, and a porphyritic chondrule was produced. There are also other complications involving cooling rate effects.

There are three general classes of models to explain the chemical fractionations I have discussed. Recently some have suggested that the fractionations are presolar. Different parcels of interstellar materials came into the solar nebula, were heated and processed a bit, but formed rocks right away without much mixing with other parcels of materials. Chondrite compositions reflect the variable mean compositions of the solids that were falling in at the exact moment they formed.

The second class of model (which I favor) was outlined above. It calls for the total solids in a section through the nebula perpendicular to the equatorial plane would have a composition identical to that of CI chondrites. That some chondrites have compositions different from that of CI chondrites reflects the fact that when dust collapse occurred to form planetesimals, appreciable fractions of some components were suspended in the nebula gas well above the midplane and were not available for accretion.

A third class of model also starts with a solar composition at all locations. This is followed by a radial separation of solids toward the sun, with different particle sizes and densities having different radial velocities. The differences in the rate of drag type motion toward the sun lead to fractionations. Some models of this class are combined with concepts of solar formation via an accretion disk.

I should still mention a very important class of data—study of the three O isotopes. In Fig. 5 $^{17}O/^{16}O$ is plotted against $^{18}O/^{16}O$ in the δ notation. The ratio is normalized to that in ocean water (SMOW) and the deviations δ from unity (in per mil) are plotted. Physical or chemical fractionation of a homogeneous starting material drives sample compositions along a line of slope of 0.52 on this diagram. All terrestrial samples, whether from the mantle, the ocean, the atmosphere, or human teeth, lie along such a line—the "terrestrial fractionation line." A great discovery made in 1973 was that carbonaceous chondrites, and especially anhydrous minerals separated from them, lie along a line with a slope of about 0.94. Such a line cannot be produced by fractionation; it probably requires the mixing of materials of diverse origins.

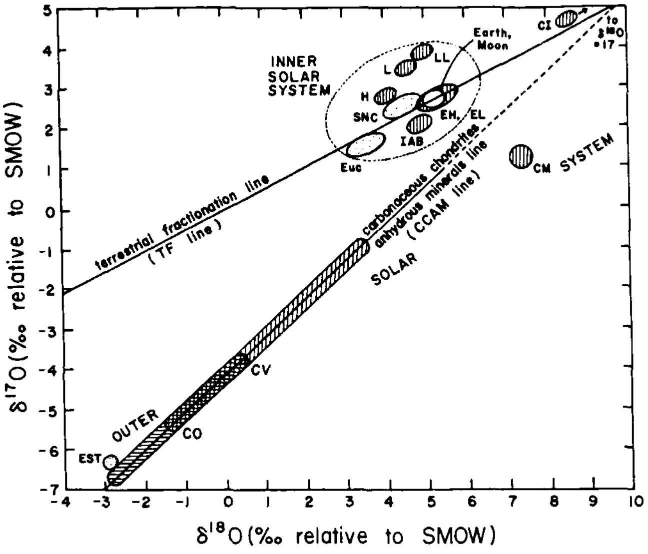

Fig. 5. Fractionation of the oxygen isotopes alters the $^{18}O/^{16}O$ ratio (represented by $\delta^{18}O$) twice as much as the $^{17}O/^{16}O$ ratio (represented by $\delta^{17}O$) and produces an array having a slope of 0.52. The line labeled "terrestrial fractionation" results from fractionation processes in terrestrial systems. The field marked "Earth, Moon" shows the estimated compositions of the mantles of these bodies. Chondrites having compositions similar to the Earth are inferred to have originated in the inner solar system. Materials plot away from the terrestrial line if they contain appreciable amounts of unevaporated interstellar solids having anomalous oxygen isotope compositions. Because the fraction of interstellar matter that escaped evaporation increases with distance from the sun, the CV, CO, and CM groups are inferred to have formed in the outer solar system. (Data from publications by R. N. Clayton, T. Mayeda, and colleagues.)

Chondrites fall into two general categories on an O-isotope diagram. The groups in the first category were probably processed at low temperatures in the solar nebula. These groups probably formed in the outer solar system far from the sun. The groups in the other category tend to cluster around the position of the bulk Earth on the terrestrial fractionation line; they seem to have formed in the hotter, inner part of the solar system. This set includes the highly reduced enstatite chondrites that may have formed nearest the sun, and plot directly on the terrestrial fractionation line. The SNC meteorites that may be from Mars lie near but resolvably above the terrestrial fractionation line.

The processes that produced the chondrites must have varied (at least in magnitude) from location to location. It is plausible that these variations could have produced some compositional trends that varied more or less monotonically with distance from the sun. Figure 6 shows a trend that may reflect radial variations on the nebula.

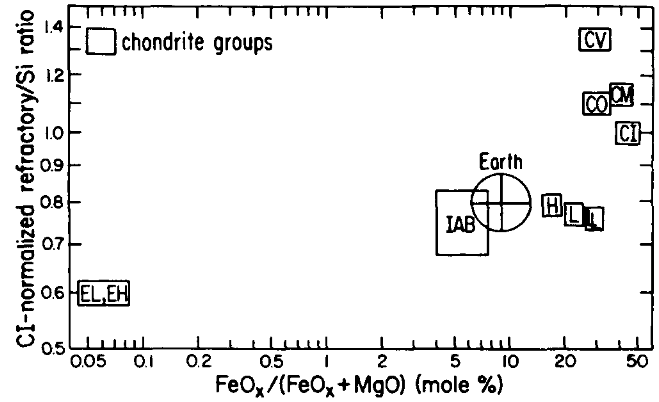

Fig. 6. Refractory-element abundances in the chondrite groups correlate roughly with degree of oxidation as indicated by FeO$_x$/(FeO$_x$ + MgO) ratio; the latter ratio is expected to increase with increasing distance from the sun. The circle gives an estimate for the bulk Earth composition. This diagram suggests that the enstatite clan formed nearest the sun and that the carbonaceous chondrites formed farthest from the sun. The chondritic inclusions in IAB irons may be the materials formed nearest to 1 AU.

Chondrite refractory lithophile abundances increase with degree of oxidation measured by FeO/(FeO + MgO). The higher the final temperature of equilibration with nebular gas, the more oxidized the materials. Chondrites formed farthest from the sun were the last to accrete and thus equilibrated with nebula gases to the lowest temperature. The enstatite chondrites formed near the sun are reduced because their coarser grains last equilibrated with nebula gases at high temperatures.

The refractory lithophile trend can also be explained in terms of increasing distance from the sun. If planetesimals formed from those materials that had managed to settle to the nebular midplane, then the refractory lithophile carrier is expected to increase in relative size as the refractory abundance of the group increases. This is precisely what is observed petrographically, and is consistent with the picture that the fraction of presolar material that failed to evaporate increased with increasing distance from the sun, and that this unevaporated material was relatively coarse.

In the future we will make more rapid progress if there is closer collaboration between astrophysicists and meteorite researchers to generate plausible nebula models, models that are designed to deal with the quantitative interpretation of meteoritic evidence, rather that the qualitative fashion in use today. We also need a much greater experimental effort at characterizing all the different components in those chondrites that suffered little alteration, those that retain the record of nebular processes with good fidelity. We should continue the isotopic characterization of strange and unusual components, since these sometimes preserve an isotopic record of interstellar origin. We must continue to use thermochemical data to explain the properties of meteorites, but we must make a greater effort to incorporate kinetics in our calculations. By using kinetics we may abe able to define nebular cooling rates recorded in individual mineral grains or calculate the maximum or minimum temperatures that were imprinted on such grains.

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INVITED TALK

COSMOCHEMICAL TRENDS OF VOLATILE ELEMENTS IN THE SOLAR SYSTEM

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INTRODUCTION

Chemical interactions between gases and grains in the solar nebula played a central role in establishing the presently observed volatile element inventories of the planets, their satellites, and the other bodies in the solar system. These interactions may have taken several forms. For example, gas-grain reactions exemplified by the sulfurization and oxidation of Fe-alloy grains, the hydration of reactive silicates, and the enclathration of C- and N-bearing gases into water ice are generally believed to have incorporated chemically reactive volatiles into solid planet-forming materials. Other thermochemical reactions, such as the synthesis of organic molecules from nebular H_2 and CO via Fischer-Tropsch-type reactions, were probably catalyzed by active grain surfaces (e.g., Fe-alloy grains). The catalysis of isotopic exchange reactions (e.g., D/H exchange) by appropriate grain surfaces has also been suggested. Finally, the extent of evaporation and thermal reprocessing of different types of presolar grains probably influenced the abundance and distribution of chemically and/or isotopically anomalous materials incorporated into meteorites, comets, and (possibly) asteroids during their formation.

Theoretical models of these different types of gas-grain chemical interactions must take into account kinetic as well as thermodynamic constraints. Indeed, the importance of some types of gas-grain interactions is almost completely determined by kinetic factors. However, much of the published theoretical work in this area (e.g., *Barshay and Lewis*, 1976; *Grossman and Larimer*, 1974) has dealt only with thermodynamic models of gas-grain chemistry. This review therefore concentrates on kinetic constraints relevant to gas-grain chemical interactions in the solar nebula. The abundant, chemically reactive volatiles H, O, C, N, and S are emphasized; however, less abundant volatiles such as P, Cl, and F are discussed where appropriate. Cosmochemical trends in the distribution of the noble gases have been recently reviewed by *Pepin* (1987) and are not considered here.

HIGH-TEMPERATURE GAS-GRAIN CHEMICAL INTERACTIONS

The water ice condensation curve (see Fig. 1) is taken as the dividing line between high- and low-temperature gas-grain chemical interactions in the solar nebula. At higher temperatures, grains that are mostly metal and/or silicate in composition are interacting with the nebular gas, while at lower temperatures predominantly icy grains are interacting with the solar nebula gas. However, in both cases the extent (and importance) of these reactions are controlled by the rate at which the relevant chemical reaction can proceed relative to the rate at which the grain is being mixed to a cooler (and thus thermochemically inactive) region of the nebula or relative to the rate of overall cooling of the solar nebula.

Denoting the characteristic chemical time constant as t_{chem} and the characteristic mixing (or overall cooling) time constant as t_{mix}, the condition for gas-grain thermochemical equilibrium is given by the inequality

$$t_{chem} < t_{mix} \tag{1}$$

Equation (1) is favored by high temperatures, slow nebula mixing rates (or slow overall cooling rates), small grain sizes, and slow accretion/coagulation rates for the grains. However, what are the specific conditions favoring this inequality for the various gas-grain reactions of interest?

A lower limit to t_{mix} has generally been estimated as $t_{mix} \sim 3H/V_s \sim 10^8$ sec, where H is the radial density scale length and V_s is the sound speed in the solar nebula (e.g., see *Prinn and Fegley*, 1987). An upper limit to t_{mix} has generally been equated to the lifetime of the solar nebula. This lifetime is approximately 10^{13} sec in currently accepted nebular models (e.g., *Cameron*, 1985; *Lin and Papaloizou*, 1985; *Morfill et al.*, 1985). Thus, gas-grain interactions with a chemical time constant $t_{chem} > 10^8$ sec may be quenched in a turbulent, rapidly mixed region of the nebula but these interactions will certainly be quenched (irrespective of nebular mixing rates) if $t_{chem} > 10^{13}$ sec, the lifetime of

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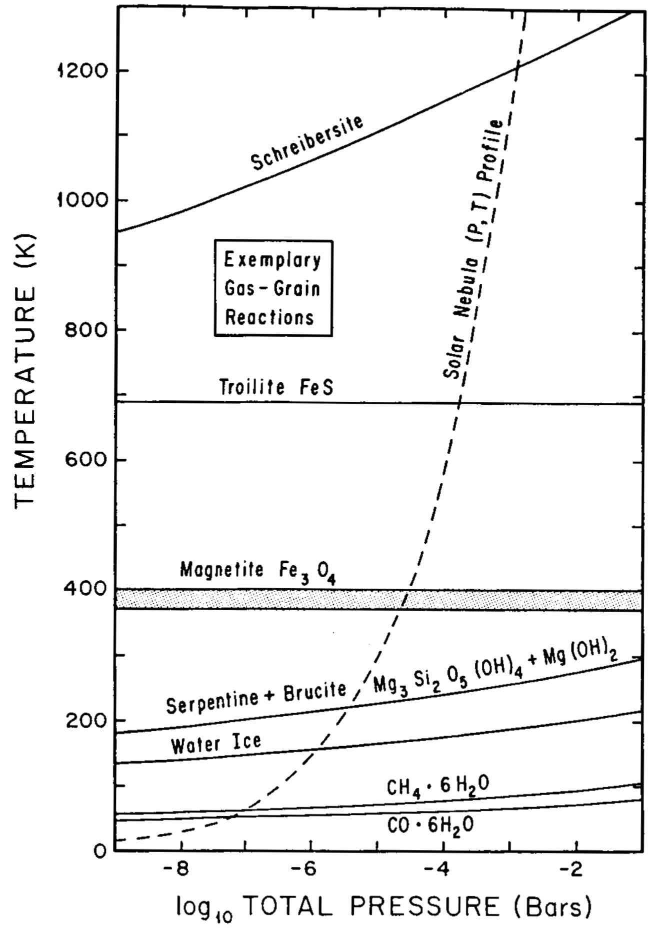

Fig. 1. Thermodynamic stability fields for exemplary gas-grain chemical interactions in the solar nebula. The solar nebula (P,T) profile is one used by *Prinn and Fegley* (1987) and is conversant with profiles in generally accepted solar nebula models. The shaded region for magnetite illustrates the range of formation temperatures appropriate for all carbon being present as either CO or CH_4. Similar ranges for serpentine formation and water ice condensation are smaller and are illustrated in Fig. 3. Curves for the formation of both CH_4 and CO clathrate are displayed; however, CO clathrate is predicted to form if CO is the dominant carbon-bearing gas and CH_4 clathrate is predicted to form if CH_4 is the dominant carbon-bearing gas.

the solar nebula. The estimation of chemical time constants for several representative types of gas-grain interactions will now be discussed.

Retention of Chemically Reactive Volatiles

Thermochemical models of solar nebula chemistry (e.g., Fig. 2, taken from *Barshay*, 1981) predict that retention of chemically reactive volatiles such as H_2O, S, P, etc. occurs by reaction of nebular gases with one or more solid phases under conditions of complete gas phase, gas-solid, and solid-solid chemical equilibrium. Although this assumption probably becomes more realistic with increasing temperature, it no longer holds at (or near) room temperature where abundant volatiles such as H_2O are predicted to be incorporated into solid grains.

This failure is easily demonstrated using literature data on cation diffusion in minerals and the scaling relation $r^2 \sim Dt$ where r is the radius of a spherical grain, D is

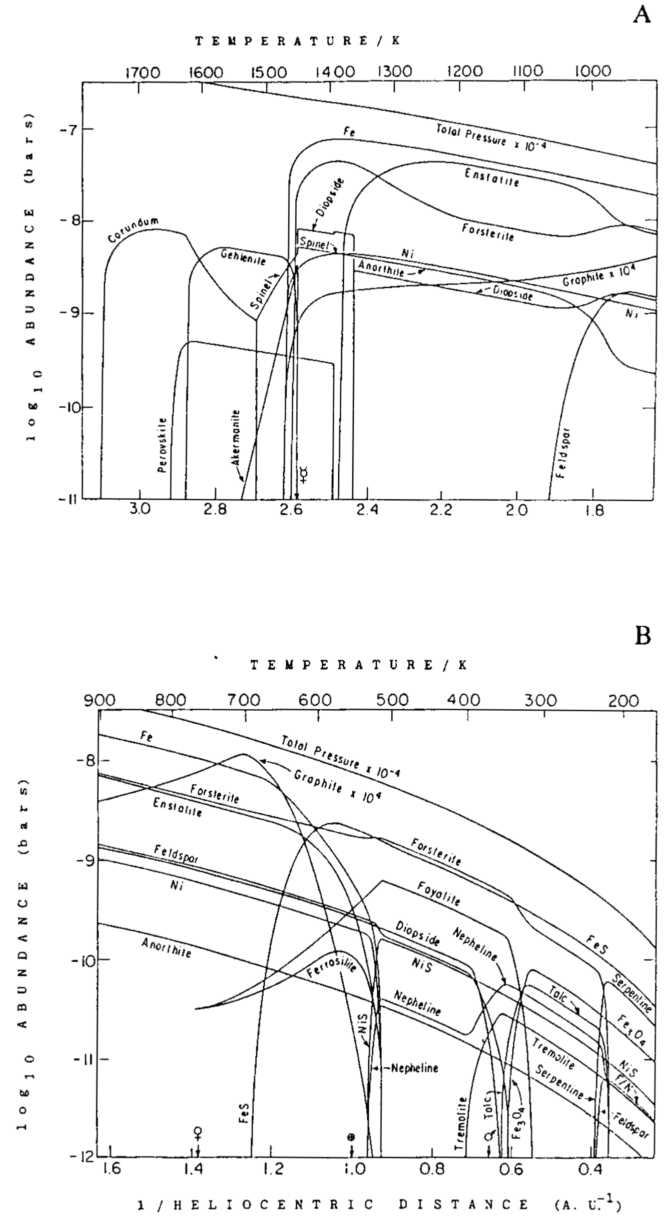

Fig. 2. Thermochemical model of chemistry in the inner regions of the solar nebula. The abundances of different volatile-bearing and major-element phases for the assumption of complete gas phase, gas-solid, and solid-solid thermochemical equilibrium are displayed along the (P,T) profile used in Fig. 1. The astrological symbols for Mercury, Venus, Earth, and Mars are shown at the appropriate places on the distance scale, which is in inverse astronomical units (A.U.$^{-1}$) (after *Barshay*, 1981).

the diffusion coefficient (with units of $cm^2\ sec^{-1}$) and t is time. The results presented in Fig. 2 show that the formation of hydrated silicates by reactions such as

$$\underset{\text{forsterite}}{Mg_2SiO_4(s)} + \underset{\text{enstatite}}{MgSiO_3(s)} + 2H_2O(g) = \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4(s)} \quad (2)$$

require the diffusion of Mg and Si between olivine and pyroxene at temperatures of 200 to 400 K. If this diffusion is as rapid as Fe-Mg diffusion in olivine [taking $D = 6.3 \times 10^{-3} \exp(-28{,}780/T)\ cm^2\ sec^{-1}$ from *Misener*, 1974], if both silicates are in intimate contact (e.g., in the same grain) for long time periods, and if the (composite) silicate grain is as small ($r \sim 0.1\ \mu m$) as fine-grained meteorite matrix then the required diffusion time is $\sim 10^{23}$ sec at 400 K and $\sim 10^{55}$ sec at 200 K. These times are significantly greater than the lifetime of the solar nebula ($\sim 10^{13}$ sec) and the age of the solar system ($\sim 10^{17}$ sec).

In reality, of course, the situation in the solar nebula may not have been as favorable as assumed above. Different minerals may not have been in intimate contact (especially for long time periods), accretion and coagulation may have produced larger grains on relatively short timescales, and solid-state diffusion (bulk and grain boundary) may have been quenched at these low temperatures. Thus, it appears very probable that solid-state chemical equilibrium cannot be reached under the (P,T) conditions postulated for water retention in currently accepted solar nebula models. As a consequence, the hydration of monomineralic silicate grains, exemplified by the reactions

$$2Mg_2SiO_4(s) + 3H_2O(g) = Mg_3Si_2O_5(OH)_4(s) + Mg(OH)_2(s) \quad (3)$$

$$4MgSiO_3(s) + 2H_2O(g) = Mg_3Si_4O_{10}(OH)_2(s) + Mg(OH)_2(s) \quad (4)$$

producing serpentine + brucite and talc + brucite, may be the only pathway for incorporating significant amounts of H_2O into solid grains prior to water ice condensation. The serpentine + brucite formation temperature calculated for reaction (3) is illustrated in Fig. 1. The talc + brucite formation temperature is ~25° higher at all pressures and is not shown.

A scaling analysis of another solid-state reaction, the incorporation of FeO into silicates, leads to similar conclusions. Thermochemical models (e.g., *Grossman*, 1972; *Barshay and Lewis*, 1976) predict that FeO incorporation into silicates occurs via the net reaction:

$$2MgSiO_3(s) + 2Fe(s) + 2H_2O(g) = Fe_2SiO_4(s) + Mg_2SiO_4(s) + 2H_2(g) \quad (5)$$

The calculations of both groups show that FeO-bearing silicates containing appreciable fayalite contents (~20 mol. %) are not formed until temperatures of 500 K or slightly lower. For comparison, the mean fayalite contents of the ordinary chondrite groups are 19% for H-chondrites, 25% for L-chondrites, and 28% for LL-chondrites (*Rubin et al.*, 1987).

Again assuming that the two reacting solids are in intimate contact for long time periods and a small grain size ($r \sim 0.1\ \mu m$), a solid-state diffusion time equal to the nebular lifetime of 10^{13} sec requires $D \geq 10^{-23}\ cm^2\ sec^{-1}$. However, at the reaction temperature (500 K), the diffusion coefficient for Fe-Mg diffusion in olivine is only $D \sim 10^{-27}\ cm^2\ sec^{-1}$. The cationic diffusion in olivine is probably more rapid than Fe-Mg diffusion between enstatite and metal to form olivine at these low temperatures. If this is the case, then it is also probable that the solid-state incorporation of FeO into silicates was kinetically inhibited at low temperatures in the solar nebula. The unreacted Fe grains that remain in contact with the nebular gas may then be "rusted" by reaction with water vapor

$$4H_2O(g) + 3Fe(s) = Fe_3O_4(s) + 4H_2(g) \quad (6)$$

to form magnetite.

The magnetite formation temperature is pressure-independent but is dependent on the water vapor partial pressure, which in turn varies with the distribution of carbon between CH_4 and CO. The results illustrated in Fig. 1 show the range of magnetite formation temperatures for all carbon present as CO and for all carbon present as CH_4. The distribution of carbon between CO and CH_4 also effects the serpentine formation temperature and the water ice condensation temperature, but the small variations are not shown on Fig. 1. However, they are illustrated on Fig. 3, which is discussed later.

The chemical time constants for reactions between nebular gases and monomineralic grains will now be estimated. The exemplary reactions considered are forsterite hydration to serpentine + brucite (reaction 3), iron metal oxidation to magnetite (reaction 6), and iron metal sulfurization to troilite

$$H_2S(g) + Fe(s) = FeS(s) + H_2(g) \quad (7)$$

In all three cases, the initial rate of reaction will depend on the collision rate of the reactant gas with the grain surfaces. This rate is given by

$$\sigma_i = 2.635 \times 10^{25} [P_i/(M_iT)^{1/2}] \quad (8)$$

where σ_i has units of $cm^{-2}\ sec^{-1}$, P_i is the partial pressure of reactant gas i, M_i is the molecular weight of gas i, and

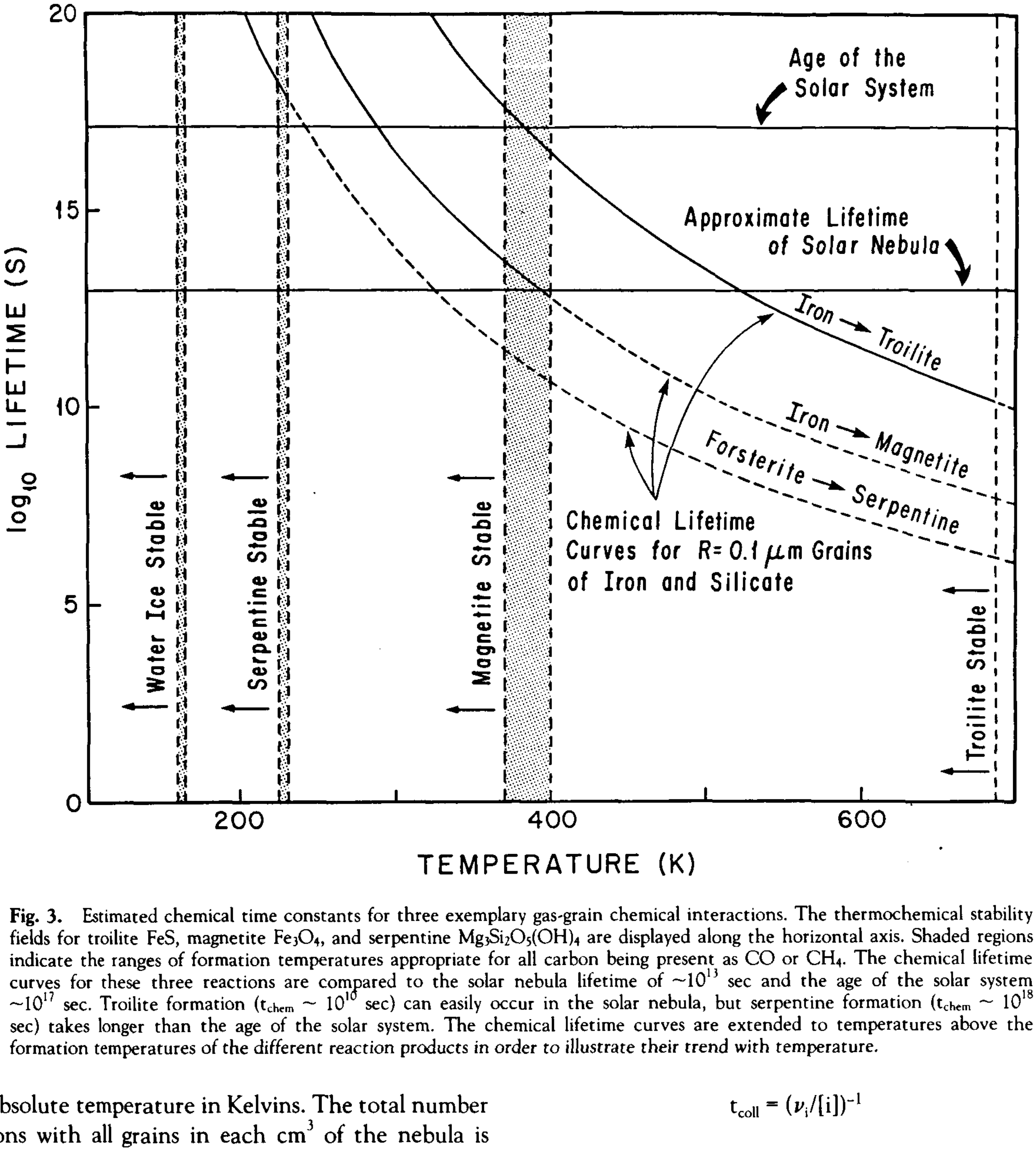

Fig. 3. Estimated chemical time constants for three exemplary gas-grain chemical interactions. The thermochemical stability fields for troilite FeS, magnetite Fe_3O_4, and serpentine $Mg_3Si_2O_5(OH)_4$ are displayed along the horizontal axis. Shaded regions indicate the ranges of formation temperatures appropriate for all carbon being present as CO or CH_4. The chemical lifetime curves for these three reactions are compared to the solar nebula lifetime of $\sim 10^{13}$ sec and the age of the solar system $\sim 10^{17}$ sec. Troilite formation ($t_{chem} \sim 10^{10}$ sec) can easily occur in the solar nebula, but serpentine formation ($t_{chem} \sim 10^{18}$ sec) takes longer than the age of the solar system. The chemical lifetime curves are extended to temperatures above the formation temperatures of the different reaction products in order to illustrate their trend with temperature.

T is the absolute temperature in Kelvins. The total number of collisions with all grains in each cm^3 of the nebula is given by

$$\nu_i = \sigma_i A \qquad (9)$$

where ν_i has units of cm^{-3} sec^{-1} and A is the total surface area of all reactant grains per each cm^3 of the nebula. The grains are assumed to be monodisperse, spherical particles that are crystalline (i.e., fully dense) and are uniformly distributed at solar abundance in the gas. The results of the present calculations, which are illustrated in Fig. 3, also assume a grain radius of 0.1 µm.

The collision time constant t_{coll} for all reactant gas molecules to collide with all grains in each cm^3 of the nebula is then

$$t_{coll} = (\nu_i/[i])^{-1} \qquad (10)$$

where [i] is the molecular number density of gas i. If every collision led to chemical reaction, equation (10) would also be the expression for the chemical time constant t_{chem}. However, only a small fraction of collisions that possess the necessary activation energy lead to chemical reaction. This fraction is given by

$$f_i = \nu_i \exp(-E_a/RT) \qquad (11)$$

where E_a is the activation energy and R is the ideal gas constant. The chemical time constant t_{chem} is thus given by

$$t_{chem} = (f_i/[i])^{-1} = t_{coll}/\exp(-E_a/RT) \qquad (12)$$

Calculated t_{chem} values for reactions (3), (6), and (7) are displayed in Fig. 3. The activation energies used in the calculations are $E_a = 70.3$ kJ mole^{-1} for vapor phase hydration of MgO to $Mg(OH)_2$ brucite (*Bratton and Brindley*, 1965; *Layden and Brindley*, 1963), $E_a = 80.3$ kJ mole^{-1} for Fe oxidation to wustite in an H_2O/H_2 atmosphere (*Turkdogan et al.*, 1965), and $E_a = 104.6$ kJ mole^{-1} for Fe sulfurization to FeS in an H_2S/H_2 atmosphere (*Worrell and Turkdogan*, 1968).

Based on these values, the estimated chemical time constants for FeS, Fe_3O_4, and serpentine formation via the gas-grain reactions considered are $\sim 10^{10}$, $\sim 10^{13}$, and $\sim 10^{18}$ sec, respectively, at the formation temperatures of 687 K, ~400 K, and ~230 K (see Fig. 3). These time constants all increase with decreasing temperature and are linearly proportional to the assumed grain radius.

The formation of FeS via reaction (7), which is estimated to take ~0.1% of the nebular lifetime, probably was an important process for sulfur retention by solid grains in the solar nebula. This process is estimated to be kinetically favorable (i.e., $t_{chem} \leq 10^{13}$ sec) down to ~525 K. The results of these kinetic calculations are thus in accord with the intuitive expectation that Fe "tarnishing" by H_2S is a rapid process.

On the other hand, the formation of serpentine + brucite by the vapor phase hydration of olivine, which is estimated to take ~10 times longer than the present age of the solar system, may not have been an important process in the solar nebula. (A similar kinetic barrier is also estimated for other low-temperature silicate hydration reactions, such as reaction (4).) In fact, the estimated t_{chem} shown in Fig. 3 for serpentine formation may be an underestimate because it is based on the activation energy for the vapor phase hydration of MgO to $Mg(OH)_2$. The vapor phase hydration of crystalline silicates such as olivine and pyroxene is a more complex process and may have a larger activation energy. The kinetic inhibition of hydrated silicate formation at low temperatures in the solar nebula is consistent with the intuitive expectation that at room temperature and below crystalline silicates will not react with low ($P \sim 10^{-9}$ bars) water vapor partial pressures. In this regard it is also important to note that extensive petrographic evidence (see, e.g., the summary by *Barber*, 1985) suggests that the hydrated silicates in CI and CM2 chondrites are products of aqueous alteration reactions on the chondrite parent bodies instead of being nebular products.

The oxidation of Fe grains by water vapor to give Fe_3O_4, which has an estimated chemical time constant $t_{chem} \sim 10^{13}$ sec at the magnetite formation temperature, appears to be an intermediate case. Again, intuition suggests that "rusting" is a rapid process which should proceed at least until constrained by diffusion through the Fe_3O_4 product layer. However, taken at face value, the estimated chemical time constant implies at least some kinetic inhibition of reaction (6), especially for magnetite formation at ~370 K when CO remains the dominant carbon-bearing gas in the solar nebula. Because the t_{chem} for Fe_3O_4 formation is based on the activation energy for wustite formation, firm conclusions regarding the kinetic favorability of reaction (6) are premature at this time. However, suitably designed experiments could resolve this question.

Surface Catalysis of Gas-Phase Reactions

Other important gas-grain chemical interactions involve the catalysis of thermodynamically favorable gas phase reactions by active and abundant grain surfaces. In particular, if Fe metal alloy grains are well mixed with the nebular gas and are catalytically active, they may catalyze the $CO \rightarrow CH_4$, $N_2 \rightarrow NH_3$, and $CO \rightarrow CO_2$ conversions; isotopic exchange reactions such as D/H exchange; and the synthesis of complex organic molecules from the CO + H_2 in the nebular gas via Fischer-Tropsch-type reactions. *Urey* (1953) first anticipated the latter possibility and proposed that the $CO \rightarrow CH_4$ conversion in the solar nebula "may well proceed through graphite or complex tarry compounds as intermediates." Experimental work by Anders and colleagues (*Hayatsu and Anders*, 1981; *Studier et al.*, 1968), who synthesized complex organic compounds analogous to those in carbonaceous chondrites via iron meteorite catalyzed Fischer-Tropsch-type reactions, has demonstrated the feasibility of Urey's proposal.

The relative importance of gas-grain catalytic interactions in the solar nebula can be assessed from estimates of their chemical time constants. This approach will first be illustrated by contrasting the t_{chem} values for the homogeneous gas phase and heterogeneous surface catalyzed conversions of CO to CH_4 and of N_2 to NH_3. These conversions occur by the net reactions

$$CO + 3H_2 = CH_4 + H_2O \qquad (13)$$

$$N_2 + 3H_2 = 2NH_3 \qquad (14)$$

As shown in Figs. 4 and 5, both reactions proceed to the right with decreasing temperature at constant pressure. However, fairly low temperatures are required for significant conversions of CO to CH_4 and of N_2 to NH_3. This is true for all currently accepted nebular pressure estimates. For example, equimolar amounts of CO and CH_4 do not result until ~710 K at 10^{-3} bars total pressure or until ~520 K at 10^{-6} bars total pressure, and equimolar abundances of N_2 and NH_3 require temperatures of ~390 K and ~270 K, respectively, at the same total pressures.

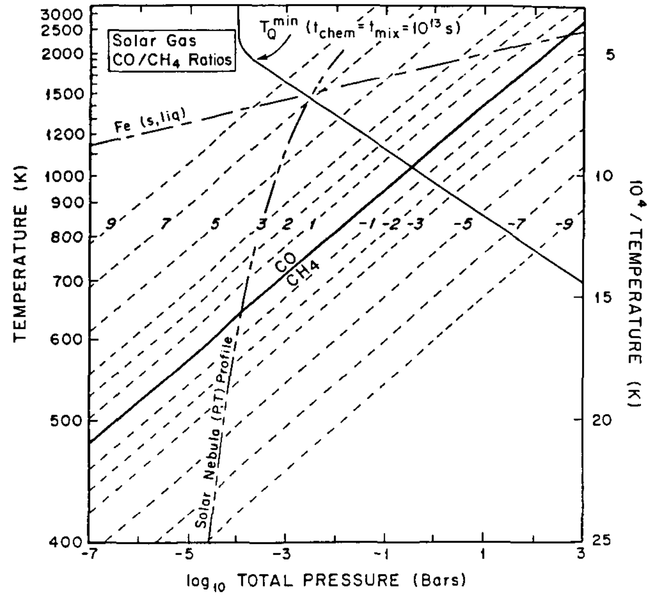

Fig. 4. Calculated (CO/CH_4) ratios at thermochemical equilibrium in solar composition gas. The solid line labelled CO-CH_4 is the boundary where the abundances of the two gases are equal; CO is more abundant to the left and CH_4 is more abundant to the right. The dotted contours labelled 9, 7, 5 . . . -5, -7, -9 are constant $\log_{10}$ (CO/CH_4) contours. The line labelled Fe(s,liq) is the Fe evaporation curve; Fe(s,liq) is stable below this line. The representative (P,T) profile from Fig. 1 is also displayed. The solid line labelled T_Q^{min} illustrates the minimum quench temperatures for homogeneous gas phase conversion of CO to CH_4 assuming that the CO chemical time constant (t_{chem}) = the longest possible nebular mixing time (t_{mix}) of 10^{13} sec (i.e., the nebular gases are mixed once during its lifetime). Shorter mixing times (i.e., more frequent mixing) results in higher quench temperatures.

However, the homogeneous gas phase pathways for both reactions (13) and (14) are kinetically inhibited at much higher temperatures before any appreciable conversion of CO to CH_4 or of N_2 to NH_3 can occur (*Lewis and Prinn*, 1980; *Prinn and Fegley*, 1987). For example, along the representative nebular (P,T) profile illustrated in Figs. 4 and 5, reaction (13) will quench at ~1470 K where (CO/CH_4) ~10^7 and reaction (14) will quench at ~1600 K where (N_2/NH_3) ~10^5. These quench temperatures are both appropriate for chemical time constants t_{chem} = 10^{13} sec; the assumption of more rapid nebular mixing (or cooling) leads to higher quench temperatures and to larger (CO/CH_4) and (N_2/NH_3) ratios.

Heterogeneous surface catalyzed pathways for the N_2 to NH_3 and CO to CH_4 conversions are more rapid than their homogeneous gas phase counterparts and allow the two conversions to proceed down to lower temperatures. Theoretical modeling of the surface catalyzed conversions is guided by industrial experience with the synthesis of ammonia and the production of synthetic fuels (e.g., *Bond*, 1962; *Dry*, 1981), which indicates that the most active and abundant catalyst present in the nebula is Fe metal. Thus, the heterogeneous surface catalysis of reactions (13) and (14) may occur throughout the temperature range where Fe metal is stable. This is limited at high temperatures by evaporation to Fe gas (e.g., see the Fe evaporation curve in Fig. 4) and at low temperatures by "rusting" to form magnetite (T ~ 370-400 K). However, the effective temperature range for Fe metal catalysis may be constrained further by the formation of FeS coatings at ~680 K or by the failure of the metal grains to remain well mixed with the nebular gas.

The specific case of the Fe metal catalyzed N_2 to NH_3 conversion was considered by *Lewis and Prinn* (1980). They concluded that the heterogeneously catalyzed reaction proceeded to much lower temperatures than the homogeneous gas phase reaction (e.g., 530 K versus 1600 K in their nebular model). However, despite proceeding to a much lower temperature, the resulting N_2/NH_3 ratio (~170) was still much greater than unity. In fact, even assuming that Fe catalysis proceeds down to the magnetite formation temperature, the N_2/NH_3 ratio will be $\gg 1$ for all currently accepted nebular models (e.g., *Cameron*, 1985; *Lin and Papaloizou*, 1985; *Morfill et al.*, 1985). Thus, even though the surfaces of Fe metal alloy grains are predicted to catalyze the N_2 to NH_3 conversion, the dominant nitrogen-bearing gas in the solar nebula remains N_2.

A similar conclusion was reached by *Mendybayev et al.* (1986) who considered the Fe metal catalyzed conversion of CO to CH_4 in the solar nebula. Based on a review of

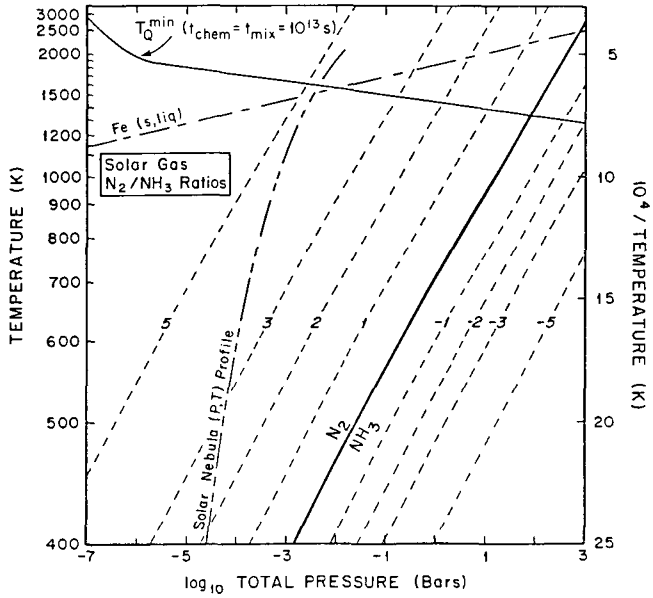

Fig. 5. As in Fig. 4 but for calculated ratios of (N_2/NH_3) at thermochemical equilibrium in solar composition gas. In this case the line labelled T_Q^{min} illustrates the minimum quench temperatures for homogeneous gas phase conversion of N_2 to NH_3.

the literature, they derived a rate equation for the reduction of CO to CH_4 on metallic iron

$$\frac{d}{dt}[CH_4] = -\frac{d}{dt}[CO] = 10^{4.35} \exp(-7548/T)\, P_{H_2} \quad (15)$$

where P_{H_2} is in atmospheres and the rate is in molecules per active site per second. The chemical time constant t_{chem} for Fe catalyzed conversion of CO to CH_4 is given by

$$t_{chem} = [CO] / \frac{d}{dt}[CO] \quad (16)$$

where [CO] is the CO molecular number density per cm^3. Taking the canonical number of $\sim 10^{15}$ active sites per cm^2 surface and assuming an iron particle radius of 100 μm, *Mendybayev et al.* (1986) calculated that the heterogeneously catalyzed reaction quenches at ~750 K where $(CO/CH_4) \sim 10$ in their nebular model. It should however be noted that their quench temperature apparently refers to $t_{chem} = t_{mix} \sim 10^{9.5}$ sec, instead of to the nebular lifetime of $\sim 10^{13}$ sec.

A similar treatment by *Prinn and Fegley* (1987), who utilized a slightly different rate equation, gives a quench temperature of ~900 K and $(CO/CH_4) \sim 10^{3.8}$ for the shortest feasible mixing times ($\sim 10^8$ sec) implied by transport at 1/3 of sound speed (e.g., *Cameron*, 1978) and a quench temperature of ~520 K and $(CO/CH_4) \sim 10^{-3.5}$ for $t_{mix} \sim 10^{13}$ sec. Both these results and those of *Mendybayev et al.* (1986) should be viewed as an upper limit to the efficiency of the Fe catalyzed CO to CH_4 conversion because both groups utilized CO destruction rate constants for clean Fe surfaces. The inactivation of the Fe surface by rapidly forming carbonaceous coatings (e.g., see *Vannice*, 1982; *Krebs et al.*, 1979), which may be similar to the "tar balls" observed in interplanetary dust particles (*Bradley et al.*, 1984; *Bradley and Brownlee*, 1986), was not considered. Thus, CH_4 formation probably did *not* proceed down to the lowest temperatures given by the models.

The more likely course of events, which is indicated by the presence of carbonaceous material in some meteorites and of "tar balls" in interplanetary dust particles, is the Fe catalyzed synthesis of complex organic molecules from CO + H_2 in the nebular gas via Fischer-Tropsch-type reactions (e.g., *Urey*, 1953; *Studier et al.*, 1968; *Hayatsu and Anders*, 1981). Net reactions such as

$$(2n+1) H_2 + nCO = C_nH_{2n+2} + nH_2O \quad (17)$$

$$(n+1) H_2 + 2nCO = C_nH_{2n+2} + nCO_2 \quad (18)$$

$$2n\, H_2 + nCO = C_nH_{2n} + nH_2O \quad (19)$$

$$nH_2 + 2nCO = C_nH_{2n} + nCO_2 \quad (20)$$

$$2nH_2 + nCO = C_nH_{2n+1}OH + (n-1) H_2O \quad (21)$$

$$(n+1) H_2 + (2n-1)CO = C_nH_{2n+1}OH + (n-1) CO_2 \quad (22)$$

which exemplify the Fischer-Tropsch synthesis of alkanes, alkenes, and alcohols, respectively, as well as similar reactions forming acetylenic and aromatic compounds, will proceed spontaneously in the presence of a suitable catalyst such as Fe or Ni (e.g., *Bond*, 1962).

The available simulation experiments (e.g., *Studier et al.*, 1968; *Hayatsu and Anders*, 1981) and the industrial literature (e.g., *Dry*, 1981) provide guidelines for estimating the chemical time constants of Fischer-Tropsch-type reactions in the solar nebula. Assuming that monodisperse, spherical Fe metal grains are dispersed at solar abundance in the nebular gas and that their surfaces are covered with sorbed hydrogen, then equation (12) can be used to estimate t_{chem} for converting CO into organic molecules. Taking an activation energy of ~90 kJ $mole^{-1}$, conversant with the literature values, and again assuming 100 μm radius Fe grains, equation (12) indicates that ~10% of all CO could be converted to organics in the nebular lifetime of $\sim 10^{13}$ sec if catalysis was effective down to ~510 K. The much smaller 0.1 μm radius Fe grains considered earlier would continue catalyzing Fischer-Tropsch conversion of this much CO down to ~440 K. These considerations in concert with the extensive observational evidence for carbonaceous matter in the solar system (e.g., see *Prinn and Fegley*, 1987) and the available simulation experiments suggest that surface catalyzed Fischer-Tropsch-type reactions played an important role in solar nebula chemistry.

Survival of Presolar Grains

Another important class of gas-grain chemical interactions are those controlling the survival of presolar grains. These reactions can take several different forms. Isotopically anomalous materials (e.g., D-rich phases) may back-exchange with the nebular gas and thus become less anomalous or isotopically "normal" as they tend toward equilibrium at the ambient temperature. Thermally labile phases (e.g., icy materials) may evaporate with increasing temperature until they eventually disappear. Chemically anomalous grains, which are out of thermochemical equilibrium with the nebular gas, may be thermally reprocessed with increasing temperature until they no longer preserve chemical and/or isotopic signatures of their presolar origin. In particular, presolar grains such as carbides, nitrides, and sulfides, which originally formed in chemically reducing environments (e.g., carbon stars) will be oxidized at high temperatures in the nebular gas. Their survival will therefore depend on their rate of oxidation versus their rate of removal to a thermochemically inactive region, for example, by mixing to cooler regions or by accretion into a meteorite parent body.

The recent report of interstellar SiC grains in the Murray carbonaceous chondrite (*Bernatowicz et al.*, 1987; *Zinner et al.*, 1987) illustrates the relevance of these theoretical arguments. Silicon carbide is thermodynamically unstable in solar composition gas and will be oxidized via the net reaction

$$SiC(s) + 3H_2O = SiO_2(s) + CO + 3H_2 \quad (23)$$

at high temperatures in the solar nebula. The protective silica coating, which inhibits further oxidation by diffusion constraints, can also undergo reaction itself. It may either evaporate by reaction with H_2

$$SiO_2(s) + H_2 = SiO + H_2O \quad (24)$$

or react with more refractory metal vapors such as Mg

$$SiO_2(s) + 2Mg + 2H_2O = Mg_2SiO_4(s) + 2H_2 \quad (25)$$

The former reaction tends to destroy the protective oxide coating while the latter reaction tends to replace it with a more refractory coating. Thus, the survival of SiC grains is dependent on the rates of three different gas-grain chemical interactions. Quantitative estimates of the conditions required for survival of SiC grains in the solar nebula are presently unavailable. However, this information can be obtained from experimental work analogous to that employed in corrosion studies of SiC-based ceramics.

LOW-TEMPERATURE GAS-GRAIN CHEMICAL INTERACTIONS

The major types of gas-grain chemical interactions that occur at temperatures below the water ice condensation curve will now be reviewed. The discussion will be brief because similar topics have recently been considered by *Lunine and Stevenson* (1985). Furthermore, the initial condensation of icy grains or of low-temperature compounds such as NH_4HCO_3, both of which are grain formation processes, will not be discussed.

The interactions of interest, which involve predominantly icy grains, fall into two categories: (1) formation of hydrates such as $NH_3 \cdot H_2O$ and (2) formation of clathrates such as $CO \cdot 6H_2O$ or $CH_4 \cdot 6H_2O$. Figure 1 illustrates the thermodynamic stability fields for these two clathrates. The CO clathrate is predicted to form when the dominant carbon-bearing gas in the solar nebula remains CO, while the CH_4 clathrate is predicted to form when CH_4 is the dominant carbon-bearing gas. However, as discussed earlier, the former case is more likely. Similarly, the predicted dominance of N_2 over NH_3 means that formation of $NH_3 \cdot H_2O$ is probably an insignificant process. The small amounts of NH_3 are predicted to form NH_4HCO_3 instead and the N_2 is predicted to form a clathrate at temperatures comparable to those required for $CO \cdot 6H_2O$ formation (*Lewis and Prinn*, 1980).

The important point illustrated by Fig. 1 is that clathrate formation in the solar nebula is predicted to occur at low temperatures and low pressures where kinetic inhibition of the process may be important (especially for large ice grains). This can be illustrated using equation (12) to estimate the chemical time constant for $CO \cdot 6H_2O$ formation. In this case, the collision lifetime for 6% of all CO (the maximum amount of CO that can be clathrated before running out of H_2O) to collide with 1-μm-radius ice grains is $\sim 4 \times 10^4$ sec for the nebular model displayed in Fig. 1. The activation energy for clathrate formation must then be $\lesssim$ 8 kJ mole^{-1} for the chemical time constant $t_{chem} \lesssim 10^{13}$ sec, the nebular lifetime. For comparison, the activation energy for HF diffusion through ice is $\sim$19 kJ mole^{-1} and the activation energies for facile high-temperature gas-grain interactions such as FeS formation are $\sim$105 kJ mole^{-1} (*Haltenorth and Klinger*, 1969; *Worrell and Turkdogan*, 1968). Thus, unless the activation energy for clathrate formation is very low, extensive clathration (especially of large icy grains) will probably be kinetically inhibited at low temperatures and pressures in the solar nebula. *Lunine and Stevenson* (1985) reached a similar conclusion on the basis of more detailed calculations.

The kinetic inhibition of clathrate formation implies that the carbon and nitrogen inventories of outer solar system bodies were supplied by other reservoirs such as carbonaceous matter or by solid ices of CO, N_2, etc. *Prinn and Fegley* (1987) have discussed these issues in some detail.

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

The current theoretical models of gas-grain chemical interactions in the solar nebula are still in a developmental stage. Nevertheless, the results of these models tend to reinforce several basic conclusions, which are listed below in order of decreasing certainty.

1. Gas-grain chemical interactions in the solar nebula took several different forms. These included the incorporation of chemically reactive volatiles into solid planet-forming materials, the catalysis of gas phase reactions, and

the evaporation and thermal reprocessing of presolar grains.

2. Gas-grain chemical interactions proceeded at different rates and thus required different amounts of time to approach thermochemical equilibrium. The interactions requiring extensive solid-state diffusion (especially at low temperatures) probably were least likely to approach equilibrium. On the other hand, interactions between monomineralic grains and the gas phase (especially at high temperatures) probably were most likely to approach equilibrium. In either case the nebular lifetime of $\sim 10^{13}$ sec defines the maximum time available to reach equilibrium.

3. Kinetically feasible gas-grain interactions in the solar nebula include simple volatile retention reactions such as schreibersite Fe_3P and troilite FeS formation. Kinetically inhibited gas-grain chemical interactions in the solar nebula include the formation of hydrated silicates and FeO incorporation into silicates. Rusting of Fe to form Fe_3O_4 may or may not be kinetically inhibited; intuition implies this reaction should be fairly rapid.

4. Catalysis of gas phase reactions by grain surfaces was important in some instances. In particular, the synthesis of complex organic molecules from nebular CO + H_2 via Fischer-Tropsch-type reactions appears kinetically feasible. The existing laboratory experiments (e.g., *Hayatsu and Anders*, 1981) indicate that Fischer-Tropsch-type reactions were an important source of at least some of the organics found in meteorites.

5. The survival of chemically reduced presolar grains, such as SiC, was dependent on the rate of oxidation by nebular water vapor. Three different types of chemical reactions (formation of a silica layer, evaporation of this layer, and reaction of this layer forming more refractory material) are involved.

6. Low-temperature gas-grain chemical interactions such as clathrate formation may have been kinetically inhibited in the solar nebula. However, sufficiently low activation energies ($\lesssim$ 8 kJ mole^{-1}) would allow enclathration of at least micron-sized ice grains to proceed over the nebular lifetime.

It is likely that a combination of experimental, observational, and theoretical studies in some key areas will increase our knowledge of gas-grain chemical interactions in the solar nebula. The following studies appear to be especially significant:

1. Laboratory studies of the kinetics of important gas-grain chemical interactions such as volatile retention reactions, grain catalyzed reactions, and presolar grain destruction reactions. Specific examples include the vapor phase hydration of anhydrous silicates, Fischer-Tropsch-type synthesis of organic molecules, and oxidation of SiC by water vapor.

2. Theoretical studies of the interplay between dynamics and chemistry in the solar nebula with an emphasis on the kinetic feasibility of various types of gas-grain chemical interactions. Such studies would presumably benefit from the laboratory studies suggested above.

3. Continuation of detailed observational studies of the chemistry, isotopic anomalies, and mineralogy of primitive, little-metamorphosed meteorites. Topics of particular interest include the nature and isotopic composition of organic molecules; the abundance, isotopic composition, and *in situ* characterization of presolar grains; and the chemistry and textural relationships of possible nebular products (e.g., hydrated silicates, magnetites, FeO-rich olivines).

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P8

INVITED TALK

TERRESTRIAL VERSUS GIANT PLANET FORMATION

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INTRODUCTION

Given a solar nebula surrounding the early protosun, containing dust grains that have already undergone growth through collisions to about centimeter-size, we consider here the question of the formation of the terrestrial and giant planets. In contrast to the usual approach of emphasizing how well we understand a problem, this talk will accentuate the uncertainties and areas where more work needs to be done. Also, the emphasis will be on the dynamics of planetary formation, because profound problems still exist in this area, and because it seems most logical to concentrate first on the dynamical questions involved with assembling the planets before putting too much effort into the detailed chemical and geological consequences of certain formation mechanisms. Finally, this talk will aim to be comprehensive rather than selective, thereby leaving the task of choosing the most significant problems to the working groups.

The level of geochemical sophistication of this talk can be surmised from the following description of the planets. We know of only two basic types of planets: the terrestrial planets (TP), composed primarily of Fe, O, Si, and Mg, and the giant planets (GP), composed largely of H, He, with lesser amounts of rock and ice.

There are also only two known ways to initiate the rapid formation of planets: through a dust disk instability (DI) and through a gas disk instability (GI). The presence of rotation in the presolar cloud ensured that the solar nebula was rotationally flattened, and provided the nebula was quiescent, the dust grains sedimented to the midplane of the gas disk and formed a much thinner dusk disk (*Weidenschilling*, 1980; *Nakagawa et al.*, 1981). Growing even kilometer-sized planetesimals through random agglomeration of centimeter-sized particles is a slow process, and gravitational instability of a dust or gas disk is an ideal way to speed up planetary growth. Growth beyond kilometer-sized bodies can proceed through the self-gravity of the individual planetesimals, but before this phase occurs, collective gravitational instability appears necessary. The dust disk instability is more properly termed the *Edgeworth* (1949)—*Gurevich and Lebedinskii* (1950)—*Safronov* (1969)—*Polyachenko and Fridman* (1972)—*Goldreich and Ward* (1973) instability, but we will simply use the phrase "dusk disk instability." This instability leads to the formation of kilometer-sized bodies on time scales of about 1000 years. The gas disk instability leads to the formation of giant gaseous protoplanets (*Cameron*, 1978) on even shorter time scales.

There are then four logical possibilities for the initiation of rapid planet formation:

DI → TP   DI → GP

GI → TP   GI → GP

The dust disk instability (and similarly the gas disk instability) has been proposed to initiate both terrestrial and giant planet formation. Mixed scenarios are also possible, where a dust disk instability leads to the terrestrial planets and a gas disk instability leads to the giant planets. So far no one has been perverse enough to propose making the terrestrial planets by gas disk instability and the giant planets by dust disk instability, but surely some opportunistic person will suggest this eventually.

GENERALIZED GRAVITATIONAL INSTABILITY

Essentially all analytical work on gravitational instability is based on a very idealized situation: the growth of linear perturbations in an isothermal, self-gravitating, rotating disk, often of infinite extent. Whether one is studying the growth of axisymmetric or nonaxisymmetric perturbations, stratified or uniform disks, viscous or inviscous flow, one typically finds that gravitational instability (i.e., exponential growth of perturbations) occurs when (ignoring factors of order unity)

$$4\pi G\rho > c^2k^2 + 4\Omega^2 + 2\,\Omega R\left(\frac{\partial\Omega}{\partial R}\right)$$

where G is the gravitational constant, ρ is the density of the gas or dust, c is the sound speed, $k = 2\pi/\lambda$ is the wavenumber of a perturbation of wavelength λ, Ω is the angular velocity of the disk, and R is the cylindrical radius. This *dispersion relation* shows that self-gravity (left-hand side) must overcome thermal pressure, rotation, and differential rotation, respectively (right-hand side), in order for instability to occur. In certain situations, some of these terms are more important than the others. For example, in the dust disk instability, the thermal pressure and differential rotation terms are negligible. In fact, when considering the growth of nonaxisymmetric perturbations in such a dust disk, perturbations growing only by azimuthal motions are unaffected by rotation, leaving the right-hand side effectively zero; nonaxisymmetric perturbations should always be unstable in this approximation.

The analytical approach has the great merit that the solution can (at least in principle) be thoroughly examined by another person, lending absolute certainty to the results, subject only to the assumptions made. On the other hand, numerical or even semianalytical solutions must rely on computer algorithms that contain a finite amount of inaccuracy and hence are more susceptible to suspicion. However, the latter methods allow one to include much more physics than one can usually handle analytically, such as growth in the nonlinear regime, nonisothermal thermodynamics, and coupled evolution of gas and dust. The absence of nonlinear effects could well be especially critical, because of an analogous situation in star formation. Jeans mass estimates are based on linearized analyses similar to the above dispersion relation, and we know that there is a lot more to understanding star formation than the Jeans instability.

DUST DISK INSTABILITY

Dust disk instability occurs following sedimentation of enough dust grains to the midplane of the solar nebula to make the dust disk density exceed the critical density given by the appropriate dispersion relation. Thermal support is thought to be almost nonexistent for dust grains because collisions between grains are supposed to damp relative motions to the order of 10 cm s^{-1}. Note, however, that the very concept of a sound speed for dust grains is called into question by the fact that sticking fractions of order unity are often assumed when treating dust grain collisions, which is rather different from the elastic collisions envisioned in the kinetic theory of gases. Sticking fractions that are different for rocky and icy dust grains could very well affect growth rates in the inner and outer solar nebula.

Goldreich and Ward (1973) envisioned the dust disk instability as occurring through two stages, the first stage involving the collective break-up of the disk into large clusters of 0.1-km-sized planetesimals, and the second stage involving the evolution of these clusters into 5-km-sized planetesimals. The result in either stage is a mass distribution that appears to be dominated by bodies of a certain size. A number of questions can be raised about the planetesimal sizes that result from this process. What is the exact form of the appropriate dispersion relation; i.e., which terms are important and what are the values of their coefficients? The Goldreich and Ward analysis addressed only local axisymmetric perturbations; do global nonaxisymmetric perturbations grow faster? Should other effects be included, such as the tidal effect of the protosun (other than through the differential rotation term) and interactions with the gas that comprises the bulk of the mass of the nebula? What happens if the nebula is more massive than a minimum mass nebula? Furthermore, as the effective dust sound speed decreases through collisional damping, the analysis assumes break-up to occur on scales given by the wavelength of the first perturbations to exceed the critical wavelength. These perturbations will begin to grow, however, on a time scale that initially is (formally speaking) infinite, so that if the sound speed continues to decline, other, shorter wavelength perturbations will get a chance to grow as well. In this case, a spectrum of masses might result.

If turbulence occurs and prevents dust grain sedimentation (*Weidenschilling*, 1984; *Nakagawa et al.*, 1986), do periodic dust disk instabilities occur during times when the nebula is not turbulent? Can one then have a situation where different periods of instability yield different size bodies? How would the presence of the first generation of bodies influence subsequent periods of instability? On the other hand, if turbulent velocities due to vertical convective instability are small enough (e.g., ≈ 0.01c; *Cabot et al.*, 1987), the presence of turbulence may have little effect on dust grain sedimentation and agglomeration.

Some of these questions might appear to be insignificant on the grand scale of planet formation, but they may very well be important for phenomena that are sensitive to the details of the mass spectrum, such as the possible runaway growth of a few planetesimals.

Accumulation in Closely Packed Phase

Given a population of 5-km-sized planetesimals, the next question is how they accumulate further. This phase of evolution is termed the closely packed phase (*Wetherill*, 1980) because the bodies are so close together that their collisions are similar to those between particles-in-a-box; the fact that the planetesimals are on orbits is not too important when you have ≈ 10^{11} or more bodies in the terrestrial planet region alone. Providing that relative velocities are regulated to values that do not cause collisional fragmentation, subsequent growth can occur through collisions. Two extremes are possible: runaway accretion, where the most massive body becomes much larger than that of the second most massive body ($M_1 >> M_2$), and uniform growth, where $M_1 \approx M_2$. In the first case, one body grows at the expense of all the others, while in the second case, all bodies grow at roughly the same rate.

Runaway growth ultimately occurs because the gravitational attraction of a massive body greatly enhances its effective cross section for collisions compared to its geometrical cross section. In some limits, the gravitationally enhanced cross section can depend on the fourth or fifth power of the body's radius, instead of the second power. Work by *Stewart and Wetherill* (1987) and *Wetherill and Stewart* (1987) now implies that, to a certain extent, "runaway" accretion can occur, leading to growth of up to a 10^{26} g body in $\approx 10^5$ years in the terrestrial planet region (*Wetherill,* 1987b; cf. *Greenberg et al.,* 1978). Runaway growth seems to be further enhanced if there is a seed mass initially, e.g., $M_{1i} \approx 2M_{2i}$. If this is the case, then we may need to know the details of the mass spectrum of planetesimals that result from dust disk instability in order to better understand runaway accretion. Runaway growth also depends strongly on the eccentricities of the planetesimals; if high eccentricities (and hence large relative velocities) are maintained through orbital perturbations by a previously formed Jupiter, then runaway growth may be stifled. In this case we may need to know the relative timing of the formation of Jupiter to know if runaway growth occurred in the terrestrial planet region.

The alternative of uniform growth was found in calculations by a number of researchers, both in the absence (*Safronov,* 1969) and in the presence of the gaseous component of the nebula (*Nakagawa et al.,* 1983). Uniform growth appears to result when certain assumptions (not necessarily the most realistic) are made about the effects of mutual gravitational perturbations among the planetesimals (*Wetherill,* 1987b). In this case, eccentricities remain high enough to account for orderly growth of the entire swarm, but not so high as to result in collisional fragmentation. This is to be contrasted with the situation in the present asteroid region, where eccentricity pumping by Jupiter means that collisions are disruptive; the asteroids are gradually being ground down.

Whether runaway or uniform growth occurs, however, this phase of growth appears to terminate in $\approx 10^{25}$–10^{26} g (1000- to 2000-km-sized) planetesimals, located on nearly circular, nonintersecting orbits. No single simulation of runaway accretion is able to correctly treat the orbital dynamics all the way from the closely packed phase to fully grown planets. A runaway terrestrial planetesimal, whose orbit is circularized by the many bodies it accumulates, may deplete its Hill sphere and grow to a maximum size of about 10^{26} g. If this is true, then the question of runaway accretion in the closely packed phase, while of great interest in its own right, may not greatly affect the details of the subsequent accumulation processes.

Accumulation in Loosely Packed Phase: Runaway Growth

The loosely packed phase refers to the phase where the orbital motions of the planetesimals must be considered, because all bodies on nearby orbits have already been accumulated. Subsequent growth depends on attaining sufficiently large eccentricities (through mutual gravitational perturbations) to enable further collisions.

One basic question is how long runaway accretion can occur: Is a runaway through both closely and loosely packed phases possible? While the Hill sphere argument noted above suggests the answer is no, until a more detailed study is made, this question must remain unanswered. There are several lines of evidence that also suggest the answer is no, however. One is that if the mass spectrum produced by the dust disk instability results in seed planetesimals that grow to become the terrestrial planets, then one must ask why were there only 4 seeds (instead of say 100 or more)? Alternatively put, if there were 100 seeds, why did they produce 4 terrestrial planets instead of 1 or 10? Second, runaway accretion through both phases would imply that the Earth was accumulated almost entirely by the impact of relatively small bodies. In this case, much of the heat of impact is likely to be lost to space and not trapped deep in the proto-Earth, and then it may be hard to explain the source of energy of the large-scale silicate-iron differentiation needed for formation of the iron core early in the Earth's evolution. Third, accumulation by small impacts would remove the possibility of forming the Earth's moon by a single giant impact, an idea that perhaps has enough merit to be used as an argument that giant impacts *must* have occurred (e.g., *Boss,* 1986a; *Stevenson,* 1987).

Accumulation in Loosely Packed Phase: Terrestrial Planet Region

Given these concerns about runaway growth all the way to planetary size, let us consider the alternative of a loosely packed phase, starting from uniform initial conditions ($M_1 \approx M_2 \approx 10^{25}$ g). Here mutual gravitational perturbations must raise orbital eccentricities enough for collisions to occur. At the same time, if the eccentricities are too large, the collisions will result in fragmentation rather than growth. It has been shown, however, that eccentricities in this phase are self-regulated to values ($v_{relative} \approx v_{escape}$) allowing continuous growth, rather than stalling by either fragmentation or isolation on nonintersecting orbits (*Safronov,* 1969; *Wetherill,* 1980).

Simulations of this phase have shown that one can produce a population of bodies that looks rather similar to the terrestrial planets in about 10^7–10^8 years (e.g., *Wetherill,* 1985). In comparison to earlier ideas involving steady growth from bodies in well-defined "feeding zones," the evolution is extremely stochastic, and involves extensive radial migration of bodies throughout the terrestrial planet region. The Earth, for example, might be accumulated out of planetesimals from much of the terrestrial planet region. This mixture would tend to erase any primordial compositional gradient that might have been produced as a result of earlier processes (such as thermal gradients) in the solar nebula.

Collisional fragmentation is likely to be of some importance in this phase, considering the large relative velocities characterizing the impacts. Not much is known about these events at present, though they are being actively investigated in connection with the giant impact model of lunar formation (*Benz et al.*, 1987). On the other hand, providing that the growing protoplanets remain at most partially molten, their intrinsic viscosities should be sufficient to prevent disruption by either tidal forces (*Mizuno and Boss*, 1985) or rotational fission instability (*Boss*, 1986b). The frequent occurrence of giant impacts in this phase (*Wetherill*, 1985) is potentially useful not only for lunar formation, but also for explaining the composition of Mercury as the iron-rich core of a protoplanet that has had its silicate-rich mantle largely removed in a catastrophic collision (*Wetherill*, 1987a; *Cameron and Benz*, 1987).

In spite of the large amount of work already done in this area, a few important questions remain. As far as orbital dynamics is concerned, the evolution of a swarm initially distributed throughout the entire terrestrial planet region has not yet been studied in depth; previous work (e.g., *Wetherill*, 1985) started with the planetesimals initially occupying a limited annulus around 1 AU (0.7 AU to 1.1 AU), chosen, however, to be consistent with the total energy and angular momentum of the present terrestrial planets. As far as we know, the dust disk instability and accumulation in the closely packed phase do not produce planetesimals just in this annulus, so one question is, what becomes of the rest of the rocky planetesimals? The planetesimals nearest the sun will have smaller sizes and will be subjected to more intense solar radiation, probably increasing the deleterious effects of collisional fragmentation and melting and evaporation, perhaps preventing robust growth. However, unless there is a ring structure in the solar nebula with a density minimum at Mars' orbit, the planetesimals at $\approx$ 1.5 AU should have grown nearly as rapidly as those at 1 AU; what happened to them? Did proto-Jupiter and proto-Earth somehow conspire (resonances?) to remove these bodies?

At least one other question must be mentioned. When a giant impact occurs, how much matter is vaporized and how much is ejected in the form of solid or partially molten chunks of debris? This question is of importance not only from the dynamical viewpoint of, for example, placing prelunar material in Earth orbit (*Kipp and Melosh*, 1987; *Benz et al.*, 1987), but also from the viewpoint of the thermal history of accumulating planetesimals and protoplanets. Giant impacts probably provide enough energy to differentiate an iron core as the proto-Earth is growing. Whether or not these bodies are molten, partially molten, or solid can have a strong effect on their viscoelastic properties, and this in turn can be important for dynamical processes such as tidal disruption and fission.

Accumulation in Loosely Packed Phase: Giant Planet Region

Final accumulation of the giant planets in the loosely packed phase, starting from uniform initial conditions ($M_1 \approx M_2 \approx 10^{26}$ g), runs into a formidable problem (*Safronov*, 1969): Between 10^8 and 10^{10} years are needed to form the $\approx$ Earth mass cores (*Mizuno*, 1980) needed for rapid hydrodynamic capture of the remainder of the giant planets' envelopes from the gaseous portion of the nebula (*Bodenheimer and Pollack*, 1986). These time scales are in conflict with astronomical evidence for removal of nebula gases by 10^6–10^7 years after solar formation (e.g., *Boss et al.*, 1987) at the low end, and in conflict with the age of the solar system at the high end. However, forming rock and ice cores first, and then at a critical core mass suddenly accreting gaseous mantles, means that the interior structure of the giant planets (e.g., *Pollack*, 1984; *Stevenson*, 1982b), and in particular the similarity of giant planet core masses (*Mizuno*, 1980), can be easily explained. Hence means to get around the time scale problem have been eagerly sought, ranging from the ridiculous ("Neptune has just finished forming") to the sublimed (the partially evaporated "superGanymedean puffballs" of *Stevenson*, 1984).

It is now apparent that runaway accretion to 10 Earth masses can occur in the giant planet region on time scales that are only slightly longer than in the terrestrial planet region (*Wetherill*, 1987b), given the occurrence of runaway accretion and somewhat higher nebular densities than are usually assumed (*Lissauer*, 1987; *Stevenson and Lunine*, 1987). Considering the great uncertainties in modeling the global evolution of the solar nebula (*Boss et al.*, 1987), a modest increase in density (about a factor of 10) in the giant planet region does not appear excessive. Rapid formation of Jupiter by this means could also solve the problem of having a source of gravitational perturbations large enough and early enough to prevent the planetesimals in the asteroid region from forming into a normal planet; the asteroids may simply have had the bad luck to have formed inside the water ice sublimation boundary (*Stevenson and Lunine*, 1987), and so did not have sufficient dust mass density to compete with the Jupiter region.

While this scenario certainly looks attractive, a number of questions remain. There is the question of by what means the accretion of gas by the protoplanets was terminated—

was it by nebula removal by the early solar wind, by viscous dissipation of nebula, or by tidal truncation? Can the nebula removal mechanism be made consistent with the wide variation in masses of the giant (and outer) planets (15 to 318 Earth masses for Uranus to Jupiter)?

Tidal truncation refers to the interaction of a growing giant planet with the gaseous portion of the nebula. The generation of local spiral density waves can clear a gap around the growing protoplanet, and effectively prevent further accretion of gas by the protoplanet (*Lin and Papaloizou,* 1980). In this case, the final masses of the protoplanets would depend on the details of gap clearing processes. In Lin and Papaloizou's model, for example, the final mass of Jupiter is determined by the effective viscosity of the nebula. Once gap clearing occurs, the protoplanet must move with the nebula gas; if the nebula is still being viscously accreted by the protosun, the protoplanet may be swallowed by the sun along with the gas (*Hourigan and Ward,* 1984). Saturn's rings provide a natural laboratory for understanding processes such as gap clearing, and the precise data available has led to increasingly refined theories of spiral density waves (e.g., *Shu et al.,* 1985).

Whether or not a gap is cleared depends critically on the mass of the protoplanet and on the effective viscosity (quantified by α) of the nebula gas (*Goldreich and Tremaine,* 1980; *Lin and Papaloizou,* 1986a,b; *Hourigan and Ward,* 1984; *Ward,* 1986). Through turbulent diffusion, viscous nebula gas resists being excluded from a gap. If the nebula is nearly inviscid ($\alpha \approx 0$), then even a very small planetesimal will be able to open a gap. For moderate amounts of viscosity ($\alpha \approx 10^{-3}$–10^{-4}; *Cabot et al.,* 1987), a protoplanet of size 0.1 Jupiter masses will be able to clear a gap. Only for very viscous nebulae ($\alpha \approx 1/3$) is gap clearing prevented until perhaps Jupiter mass objects are formed.

The angular momentum transport associated with spiral density waves can substantially alter the orbit of the protoplanet that causes them, provided a gap is not cleared (*Goldreich and Tremaine,* 1980; *Lin and Papaloizou,* 1986a,b; *Lissauer,* 1987). While this motion relative to the nebula gas can aid the accumulation process (*Hourigan and Ward,* 1984), there is again a danger of spiralling inward to the sun. Time scales for significant orbital motion are inversely proportional to protoplanet mass, and can be as short as 10^3–10^4 years for a Jupiter-sized object. This time scale must be compared with the time scale for growth by accretion of gas onto the 10 Earth mass cores; if the gas accretion time scale is shorter, then the protoplanet will be able to grow large enough to open a gap before it spirals inward appreciably. *Bodenheimer* (1985) estimated a time scale of $\approx 5 \times 10^4$ years for growth from 20 Earth masses to 0.2 Jupiter masses, while *Sekiya et al.* (1987) found that growth from 0.26 Jupiter masses occurred on a time scale of about 300 years. Thus it may be that once a giant protoplanet reaches 0.2 Jupiter masses, it is growing fast enough to escape orbital spiralling, but in the earlier phases, there is a real possibility of substantial orbital evolution through spiral density waves. Clearly we need a better quantitative understanding of all of these processes.

If the gas density in the giant planet region required to account for the initial runaway growth of the rock and ice cores is too large, it is possible that gravitational instability of the gaseous component could lead directly to giant planet formation, which we consider next.

GAS DISK INSTABILITY

Compared to the dust disk instability and accumulation of planetesimals theory, little work has been done on the gas disk instability and its implications. The most important study of the gas disk instability is that by *Cassen et al.* (1981), who used a particle code to determine the stability of infinitely flat, isothermal disks with surface density varying as the inverse of the radius. They found stability to depend on disk temperature (T_d) and the ratio of the disk mass (M_d) to the mass of the central protosun (M_c): Instability only occurred for disks that were very massive ($M_d/M_c = 10$) and cool ($T_d = 100$ or 300 K), or moderately massive ($M_d/M_c = 1$) and cold ($T_d = 100$ K). The instability always occurred in the outer regions rather than in the inner regions of the nebula, which implies that either gas disk instabilities could not have formed the terrestrial planets, or that substantial orbital migration inward was necessary for forming the terrestrial planets by this means. Most of all, this study supported the general belief that a massive nebula ($\approx 1 M_\odot$) is needed for gas disk instability to occur, if the sun has already formed.

Again, a number of basic questions about the gas disk instability can be posed. The most profound is whether or not the issue of stability of the nebula can be separated from that of the stability of the matter collapsing to form the protosun: Is a "snapshot" approach, with an assumed density and temperature structure and an assumed central mass, even valid? If the nebula is grossly unstable at a given snapshot of its evolution, then it was probably also unstable at an earlier epoch, and hence may have evolved in some other fashion. The most probable situation may be a nebula that is just beginning to become gravitationally unstable. Cassen has suggested that such a marginal nebular instability may then always lead to the growth and dissipation of spiral density waves, rather than to the full-blown instability presumably needed to produce discrete gaseous protoplanets. In order to resolve this question, we will need to study the combined problem of nebula stability and growth of the protosun.

Even within the context of the snapshot approach, several questions about the gas disk instability remain. What happens in nonisothermal disks, with the temperature gradient that must have been present in the early solar nebula? Does a true fluid disk behave in the same manner as a particle simulation of a fluid? How does the neglected third dimension (vertical height) affect the gas disk instability? How many gaseous protoplanets can be produced, and what is their mass spectrum?

Giant Planet Region

In part because a massive nebulae is that much harder to remove than a minimum mass nebula ($\approx 0.05M_\odot$), massive nebulae (and hence gas disk instabilities) have never been very popular. Recent observations of energetic mass loss phases in young solar-type stars may make early solar wind removal of relatively low mass nebulae somewhat more likely, but removal to infinity of a solar mass of nebula from a solar-type star seems very unlikely (e.g., *Boss et al.*, 1987). Actually, the most convenient place to dump excess nebula matter is onto the growing central protosun. If the protosun already has a solar mass of gas, of course, this is not a viable option for forming our solar system out of a massive solar nebula. If the protosun is just beginning to form, however, one might be able to remove a solar mass of nebula by dumping onto the protosun. But in this case, one runs the risk of losing any gaseous planets that have already been formed; the comments on gap formation in the previous section imply that the most massive protoplanets should clear gaps and be locked to the gas even in a highly viscous nebula. Thus protoplanets that form too early may be lost to the growing protosun. Because solar system formation is not thought to be a two-step process (i.e., the sun did not simply form first, and then have a solar nebula magically emplaced about it), gas disk instability may well have occurred early in the formation of the solar system, and led not to giant planet formation, but to enhanced addition of mass to the sun.

Several problems with the gas disk instability mechanism are brought to light by considering the interior structure of the giant (and outer) planets (*Stevenson*, 1982a). First, the peculiar similarity in core masses among these planets, independent of total masses that vary by factors of over 20, does not have any explanation in this scenario, in marked contrast to the strong appeal of the core mass trigger concept associated with the dust disk instability and planetesimal accumulation theory. Reducing envelope to core mass ratios through thermal stripping (*Cameron et al.*, 1982) unfortunately predicts that the lower ratios should occur closer to the sun, which is opposite to the situation in our solar system. Second, forming any core at all out of a nearly homogeneous sphere of nebula gas and dust may be impossible, if the core materials turn out to be miscible in metallic hydrogen. These arguments have been sufficient to dissuade many from believing in giant planet formation by this means.

Terrestrial Planet Region

Given by some means a giant gaseous protoplanet in orbit about the sun, the earlier concerns regarding orbital migration still apply (see also *Cameron*, 1979). That is, prior to gap clearing, a massive protoplanet may move relative to the nebula gas because of gravitational torques from its associated spiral density waves. While potentially disastrous if unchecked, some movement inward could bring protoplanets formed in the giant planet region into the terrestrial planet region. There they would be subjected to tidal forces from the sun and immersed in a thermal bath that would tend to evaporate their gaseous envelopes, perhaps leaving behind a rocky core resembling a terrestrial planet (*Cameron et al.*, 1982). However, such a thermal bath may have to be extremely hot in order to accomplish this envelope stripping (e.g., 3000 K at Mercury), and nebular temperatures this high cannot be produced except by the most extremely viscous nebula models (*Cameron*, 1985). It is also not clear whether envelope stripping can produce an atmosphere with the elemental and isotopic compositions of the terrestrial planets. The concerns about core formation noted above are especially cogent for making terrestrial planets out of giant gaseous planets.

Moving giant gaseous protoplanets inward from the giant planet region to the terrestrial planet region is probably preferable to trying to form giant gaseous protoplanets directly at ≈ 1 AU, because the latter process would require a nebula even more massive than those already discussed (e.g., *Wetherill*, 1980), and hence even more difficult to remove.

SATELLITES

The formation of satellites is a peripheral issue in the sense that we have a hard enough time trying to figure out how the planets were formed, much less the minor bodies that accompany them, but certainly a few comments on satellite formation are in order. Once again we will use the tactic of divide and conquer, and consider several different types of satellites.

Giant Planet Region

Giant planet satellites themselves fall into two basic types. The regular satellites tend to orbit closest to the planet, on prograde orbits of small eccentricity and inclination, and with compositions that change with orbital position in a regular fashion. The irregular satellites, obviously, disobey all of these rules. The dynamical and geological characteristics immediately suggest that the regular satellites formed in some sort of mini-solar nebula encircling the protogiant planets (*Coradini et al.*, 1981; *Lunine and Stevenson*, 1982), while the irregular satellites were formed elsewhere in the solar system (perhaps as heliocentric planetesimals) and then captured through some means (e.g., *Pollack*, 1984). A likely means for capture is through dissipation of the relative energy of motion in the dense mini-solar nebulae that produced the regular satellites. The main problem with the latter mechanism is that the timing of captures may have to be correlated with the removal of the mini-solar nebula, else the newly captured satellites might spiral inward and be lost to the central protoplanet. On the other hand, if a large population of such planetesimals passed through the mini-solar nebula in this manner, then the irregular satellites would simply be the last ones captured before mini-solar nebula dispersal.

Needless to say, many of these processes have not been studied in great detail as yet. For example, having a mini-dust disk instability occur in a portion of the solar nebula that has already undergone a global dust disk instability may not be realistic, unless a large amount of new dust grains have fallen into the solar nebula from the presolar cloud envelope, or unless temperatures in the mini-solar nebula were high enough to vaporize refractory material, so that this vapor could later recondense into grains (*Lunine and Stevenson*, 1982).

Terrestrial Planet Region

One reason the terrestrial planets do not have the large satellite systems that characterize the giant planets may be that they probably did not form as giant gaseous protoplanets, and hence did not have the extended mini-solar nebulae apparently necessary for formation of regular satellite systems and capture of irregular satellites.

If we instead look to the process of dust disk instability and planetesimal accumulation to account for the terrestrial satellites, a reasonable picture emerges. As noted previously, giant impacts appear to be a self-consistent mechanism for explaining the origin of the Moon. The fact that Venus does not have a satellite can be explained in either of two fashions. First, the one or two giant impacts experienced by Venus may not have had just the right impact parameter to result in formation of a moon in orbit about Venus (e.g., *Benz et al.*, 1987). In this case, the really remarkable fact may appear to be that the giant impact on Earth hit the right spot, but this does not appear to be a wildly improbable event (*Boss and Peale*, 1986). Second, any moon formed about Venus might have undergone orbital decay onto the Venus surface, because the Venus-moon combination may have happened to end up in a configuration where subsequent tidal evolution drove the satellite inward instead of outward.

Phobos and Deimos are so small that they tend to be ignored. A reasonable explanation for their formation is definitely lacking.

COMETS, ASTEROIDS, AND PLUTO

Finally, we come to the minor bodies on heliocentric orbits in the solar system. The comets are generally thought of as icy planetesimals formed in the giant planet region and later ejected by their much more massive siblings to cold storage in the Oort cloud (e.g., *Greenberg et al.*, 1984). As noted previously, asteroids appear to be planetesimals formed in the transition zone between regions of terrestrial and giant planet formation, whose complete accumulation was prevented by the more rapid growth of proto-Jupiter. Pluto/Charon may be an escaped satellite of one of the outer planets (specifically Neptune, whose heliocentric orbit it periodically intersects), but the question is, How did it escape?

The key bodies here are the asteroids, whose incomplete formation gives us a strong clue about planet formation. Whatever aborted their growth is probably also responsible for the puny size of Mars. Early Jupiter formation appears to solve both of these problems, and the only question is then explaining why the runaway growth that may have rapidly produced Jupiter did not equally (or more) rapidly produce a major planet in the asteroid zone. The possibility that the water ice condensation zone occurred between the asteroidal and giant planet regions is probably intimately tied up with this question, and it remains to be seen if phenomema such as diffusive redistribution (*Stevenson and Lunine*, 1987) will be able to enhance the density of icy planetesimals enough to explain this fundamental boundary for planetary formation.

CONCLUSIONS

This talk has tried to give some sense of the very many fundamental problems associated with the formation of the terrestrial and giant planets, problems that are still largely unsolved after decades of work by a relatively small but dedicated group of planetary scientists. Recent advances in our knowledge about the physical and chemical structure of the planets, about the formation of solar-type stars and their accompanying nebulae, in computational ability, and in the theoretical framework of planet formation, all imply that many of the basics necessary for solving these problems exist now. Planetary cosmogony has come of age as a serious branch of science. We can certainly hope that the next several decades of research will reveal the answers to many of these vexing questions.

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INVITED TALK

THE ATMOSPHERES OF THE EARTH AND THE OTHER PLANETS: ORIGIN, EVOLUTION, AND COMPOSITION

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PREFACE

The origin, early history, evolution, and composition of planetary atmospheres, including the atmosphere of our planet, is directly related to the origins of solar systems, in general, and to the accumulation and growth of planets, in particular. The study of planetary atmospheres is merely a continuation of the study of the same atoms and molecules that composed the solar nebula that formed the solar system some 4.6 b.y. ago. Studies of the origin, early history, evolution, and composition of planetary atmospheres provide new and unique information about the accumulation and growth of the planets and provide new insights into the conditions of the early solar system.

The study of the origin, evolution, and chemistry of planetary atmospheres provides an area of interest and relevance to several programs within the Office of Space Science and Applications (OSSA) in addition to the Planetary Exploration Division. Both the Life Sciences Division and the Earth Observation Division have interests in planetary atmospheres. The Life Sciences' Exobiology Program is concerned with the origin, early history, and evolution of the atmosphere as it pertains to the origin and evolution of life on our planet. The Exobiology Program is also interested in Mars, the outer planets, and Saturn's satellite, Titan, as possible locations for extinct or extant life or the precursor organic molecules needed for life. The Life Sciences' Biospherics Program treats life as a planetary phenomenon and considers the impact of life on the planetary environment, such as the biogeochemical cycling of elements between the biosphere and the atmosphere and the biogenic production of environmentally significant trace gases such as the gases that impact global climate. The Earth Observation Division's programs in Tropospheric Chemistry, The Upper Atmosphere, and Climate are all concerned with the chemistry and radiative properties of trace atmospheric gases and their changes with time.

Our current understanding of the composition, chemistry, and structure of the atmospheres of the other planets and the origin, early history, and evolution of the Earth's atmosphere is reviewed in this paper. The information on the atmospheres of the other planets is based on the highly successful Mariner, Viking, Pioneer, and Voyager missions to these planets. The information on the origin, early history, and evolution of the atmosphere, which is somewhat speculative, is largely based on numerical studies with geochemical and photochemical models.

INTRODUCTION

The sun, Earth, and the other planets condensed out of the "primordial solar nebula," an interstellar cloud of gas and dust, some 4.6 b.y. ago. Volatiles were the major constituent of the solar nebula. The overwhelming volatile element was hydrogen, followed by helium, oxygen, nitrogen, and carbon. Considerably less abundant in the solar nebula, but key elements in the formation of the solid planets, were the nonvolatile refractory elements, such as silicon, iron, magnesium, nickel, and aluminum. We believe that the terrestrial planets (Mercury, Venus, Earth, and Mars) formed through the processes of coalescence and accretion of the refractory elements and their compounds beginning with grains, the size of dust, to boulder-sized "planetesimals," to planetary-sized bodies. The terrestrial planets may have grown to their full size and mass in as little as 10 m.y. Volatiles incorporated in a late-accreting, low-temperature condensate may have formed as a veneer surrounding the newly formed terrestrial planets. This volatile-rich veneer resembled the chemical composition of carbonaceous chondritic meteorites, which contain relatively large amounts of water (H_2O) and other volatiles. The collisional impact of the refractory material during the coalescence and accretion phase caused widespread heating within the forming planets. The heating was accompanied by the release of the trapped volatiles through a process termed "volatile outgassing." The oxidation state and hence the chemical composition of the outgassed volatiles depended on the structure and composition of the solid planet and, in particular, the presence or absence of free iron in the upper layers of the solid planet. If the terrestrial planets formed as geologically differentiated bodies, i.e., with free iron having already migrated to the core (as a result of the heating and high temperature accompanying planetary accretion), surrounded by an iron-free mantle of silicates, the outgassed volatiles would have been composed of water vapor, carbon dioxide (CO_2), and molecular nitrogen (N_2), not unlike the chemical composition of present-day volcanic emissions. Current theories of planetary formation suggest that the Earth, Venus, and Mars formed as geologically differentiated objects. Some volatile outgassing may have also been associated with the impact heating during the final stages of planetary formation. This outgassing would have resulted in an almost instantaneous formation of the atmosphere, coincident with the final stages of planetary formation. As a result of planetary accretion and volatile outgassing, the terrestrial planets are characterized by iron-silicate interiors with atmospheres composed primarily of carbon dioxide (Venus and Mars) or molecular nitrogen (Earth), with surface pressures that range from about 1/200 atmosphere (Mars) to about 90 atmospheres (Venus). (The surface pressure of the Earth's atmosphere is one atmosphere.)

In direct contrast to the terrestrial planets, the outer planets (Jupiter, Saturn, Uranus, and Neptune) are more massive (15–318 Earth masses), larger (4–11 Earth radii), and possess multiple satellites and ring systems. The atmospheres of the outer planets are very dense and contain thick clouds and haze layers. These atmospheres are composed primarily (85–95% by volume) of molecular hydrogen (H_2) and helium (He) (5–15%) with smaller amounts of compounds of carbon, nitrogen, and oxygen, primarily present in the form of saturated hydrides [methane (CH_4), ammonia (NH_3), and water vapor] at approximately the solar ratio of carbon, nitrogen, and oxygen. The composition of the atmospheres of the outer planets suggests that they are captured remnants of the primordial solar nebula that condensed to form the solar system, as opposed to having formed as a result of the outgassing of volatiles trapped in the interior, as did the atmospheres of the terrestrial planets. It has been suggested that a thick atmosphere of molecular hydrogen and helium, the overwhelming constituents of the primordial solar nebula, may have surrounded the terrestrial planets very early in their history (during the final stages of planetary accretion). However, such a primordial solar nebula remnant atmosphere surrounding the terrestrial planets would have dissipated very quickly, due to the low mass of these planets and hence their weak gravitation attraction, coupled with the rapid gravitational escape of hydrogen and helium, the two lightest gases, from the "warm" terrestrial planets. Therefore, an early atmosphere composed of hydrogen and helium surrounding the terrestrial planets would have been extremely short-lived, if it ever existed at all. The large masses of the outer planets and their great distances from the sun (and colder temperatures) have enabled them to gravitationally retain their primordial solar nebula remnant atmospheres. The colder temperatures resulted in a "freezing out" or condensation of several atmospheric gases, such as water vapor, ammonia, and methane forming cloud and haze layers in the atmospheres of the outer planets.

THE EARTH'S ATMOSPHERE: ORIGIN, EVOLUTION, AND COMPOSITION

It is generally believed that the Earth and the rest of the solar system condensed out of an interstellar cloud of gas and dust, called the "primordial solar nebula," about 4.6 b.y. ago. The atmospheres of the Earth and the other terrestrial planets (Venus and Mars) are thought to have formed as a result of volatile outgassing: the release of trapped volatiles from the solid planet (*Walker*, 1977; *Lewis and Prinn*, 1984; *Levine*, 1985a). By contrast, the atmospheres of the giant planets Jupiter, Saturn, Uranus, and Neptune are believed to be the captured remnants of the primordial solar nebula. Some volatile outgassing and formation of the Earth's atmosphere may have been associated with the impact heating during the final stages of the formation of the Earth.

For many years it was believed that the early atmosphere of the Earth was a strongly reducing chemical mixture composed of methane (CH_4), ammonia (NH_3), and molecular hydrogen (H_2). The more recent picture envisions the early atmosphere as a mildly reducing mixture of carbon dioxide (CO_2), molecular nitrogen (N_2), and water vapor (H_2O), with only trace amounts of hydrogen (*Levine*, 1985b). This mixture is not unlike that emitted by present-day volcanoes (Table 1). There is very little question but that the Earth outgassed tremendous quantities of H_2O, CO_2, and N_2 over geological time. The question is whether

TABLE 1. Average composition of Hawaiian volcanic gas (*Walker*, 1977).

Gas	% Volume
Water vapor (H_2O)	79.31
Carbon dioxide (CO_2)	11.61
Sulfur dioxide (SO_2)	6.48
Nitrogen (N_2)	1.29
Hydrogen (H_2)	0.58
Carbon monoxide (CO)	0.37
Sulfur (S_2)	0.24
Chlorine (Cl_2)	0.05
Argon (Ar)	0.04

outgassing of CH_4, NH_3, and H_2 occurred for a short while prior to the longer period of extensive outgassing of H_2O, CO_2, and N_2. Most researchers now believe that the answer to this question is no. Clearly, the composition of the present atmosphere (Table 2) bears very little resemblance to the composition of the early atmosphere. The bulk of the H_2O that outgassed from the interior condensed out of the atmosphere, forming the Earth's vast oceans. Only small amounts of H_2O remained in the atmosphere, with almost all of it confined to the troposphere (the lowest region of the atmosphere that extends from the surface to about 10 km). At the surface, the H_2O concentration is variable, ranging from a fraction of a percent to a maximum of several percent by volume. At the top of the troposphere, H_2O has a mixing ratio in the parts per million by volume (ppmv = 10^{-6}) range. Most of the CO_2 that outgassed over the Earth's history formed sedimentary carbonate rocks [calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$] after dissolution in the ocean. The mixing ratio of CO_2 in the present atmosphere is about 340 ppmv (0.034% by volume). It has been estimated that the preindustrial (around the year 1860) level of atmospheric CO_2 was about 280 ppmv (0.028%). For each CO_2 molecule presently in the atmosphere, there are about 10^5 CO_2 molecules incorporated as carbonates in sedimentary rocks. All of the carbon presently in sedimentary rocks outgassed from the interior of the Earth and was at one time in the atmosphere in the form of CO_2. Hence, the early atmosphere may have contained orders of magnitude more than CO_2 than it presently contains. Molecular nitrogen is chemically inert, non-water-soluble (as is CO_2) and noncondensable (as is H_2O). Hence most of the outgassed nitrogen accumulated in the atmosphere over geological time to become the most abundant constituent (78% by volume). It is important to note that oxygen, the second most abundant constituent of the atmosphere (21% by volume), is not released via volatile outgassing or volcanic activity. However, oxygen may be produced from volcanic H_2O and CO_2 via photochemical processes.

TABLE 2. Composition of the present atmosphere (*Levine*, 1985b).

Gas	% Volume
Nitrogen (N_2)	78.08
Oxygen (O_2)	20.95
Argon (Ar)	0.93
Water vapor (H_2O)	Variable: 0 to few %
Carbon dioxide (CO_2)	0.034

THE ABIOGENIC PRODUCTION OF OXYGEN

The photolysis of H_2O and CO_2 served as an abiogenic source of O_2 in the early, prebiological atmosphere. The photolysis of H_2O leads to the photochemical production of O_2 via the following reactions

(1) $H_2O + h\nu \rightarrow OH + H, \lambda < 240$ nm (ν = frequency)

A small percentage (<10%) of the atomic hydrogen (H) produced by the photolysis of H_2O will eventually escape into space. The hydroxyl radical (OH) formed by the photolysis of H_2O forms atomic oxygen (O) via the reaction

(2) $OH + OH \rightarrow O + H_2O$

Similarly, the photolysis of CO_2 leads to the formation of O via

(3) $CO_2 + h\nu \rightarrow CO + O, \lambda < 230$ nm

The atomic oxygen produced in reactions (2) and (3) forms O_2 via

(4) $O + O + M \rightarrow O_2 + M$

where M is any third body. O_2 may also be formed from the products of reactions (1)–(3) via

(5) $O + OH \rightarrow O_2 + H$

Some of the O_2 produced by reactions (1)–(5) was lost via the oxidation of minerals exposed to the atmosphere during the course of weathering. O_2 was also lost by direct photolysis (reaction (6)) and by atmospheric reaction with H_2 (reaction (7)), which led to the reformation of H_2O

(6) $O_2 + h\nu \rightarrow O + O, \lambda \leq 242$ nm

(7) $2H_2 + O_2 \rightarrow 2H_2O$ (Net cycle)

Levels of O_2 in the early prebiological atmosphere were very sensitive to atmospheric levels of H_2O, CO_2, and H_2, and to the flux of incoming solar radiation, which initiates the photolysis of H_2O, CO_2, and O_2. There is reason to believe that all of these parameters may have varied significantly over geological time (*Hart*, 1978; *Canuto et al.*, 1982, 1983). The H_2O distribution in the troposphere is controlled by the saturation vapor pressure, which is regulated by the tropospheric temperature profile. Even though very large amounts of H_2O may have outgassed in the early history of our planet, it seems unlikely that the early atmosphere contained significantly more H_2O than the present atmosphere contains, since any outgassed H_2O in excess of its saturation vapor pressure would have simply condensed into cloud droplets and then precipitated out of the atmosphere. CO_2 is a different story. Prior to the formation of carbonates, the early atmosphere may have contained significantly higher levels of CO_2, perhaps orders of magnitude more CO_2 than presently found in the atmosphere (*Hart*, 1978). To assess the importance of CO_2 on early prebiological levels of O_2, we have performed photochemical calculations for the preindustrial level (280 ppmv) and for 100 times that value, a mixing ratio of 0.028 (2.8% by volume) (*Levine*, 1982). While very little is known about levels of H_2 in the early atmosphere, previous studies suggested an H_2 mixing ratio of between 1.7×10^{-5} (17 ppmv) (*Kasting and Walker*, 1981) and 10^{-3} (*Pinto et al.*, 1980). To assess the importance of H_2 on early atmospheric levels of O_2, we performed photochemical calculations over a wide range of H_2 concentrations for mixing ratios ranging from 10^{-6} to 10^{-1}.

A key parameter in the photochemical production of O_2, which is initiated by the photolysis of H_2O and CO_2, is the level of solar ultraviolet (UV) flux (see reactions (1) and (3)). Measurements of young, sun-like stars obtained with the International Ultraviolet Explorer (IUE) satellite suggest that the young sun may have emitted considerably more UV radiation than it presently emits (*Canuto et al.*, 1982, 1983; *Zahnle and Walker*, 1982), although the total visible luminosity of the young sun was only about 75% of its present value (*Hart*, 1978). The variation in UV radiation emitted by a sun-like star over its history is summarized in Table 3 (*Canuto et al.*, 1982). To assess the role of enhanced solar UV radiation on early atmospheric levels of O_2, we performed calculations over a wide range of UV levels (*Levine*, 1982).

The results of these photochemical calculations are shown in Figs. 1–4. Figure 1 shows the vertical distribution of O_2 in the early atmosphere for three different sets of calculation parameters. Profile B represents the "standard" case: $CO_2 = 1$ (280 ppmv), H_2 mixing ratio $= 1.7 \times 10^{-5}$, and solar UV $= 1$ (present level). Profile A represents a combination of parameters to give a minimum O_2 profile: $CO_2 = 1$, H_2 mixing ratio $= 10^{-1}$, and UV $= 1$, while profile C represents a combination of parameters to yield a maximum O_2 profile: $CO_2 = 100$, H_2 mixing ratio $= 1 \times 10^{-6}$, and UV $= 100$. All three calculations exhibit a similar distribution with altitude. The O_2 maximum occurs above 40 km, the region of maximum photolysis, and the O_2 minimum occurs close to the surface, away from the region of maximum photolysis.

TABLE 3. Solar ultraviolet radiation as a function of sun's age (*Canuto et al.*, 1982).

Age (Years)	Ultraviolet Enhancement
10^6	10^4
10^7	500
5×10^7	100
10^8	32
5×10^8	8
10^9	4
4.5×10^9	1

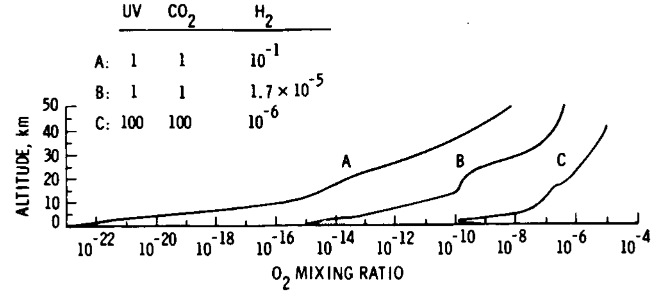


Fig. 1. Vertical distribution of O_2 in the prebiological early atmosphere for three different sets of values for CO_2, H_2, and solar ultraviolet (UV) radiation (*Levine*, 1985b).

The variation of surface O_2 mixing ratio of a function of CO_2 and H_2 for different solar UV levels is shown in Figs. 2–4. Figure 2 shows the surface O_2 mixing ratio as a function of CO_2 (for $CO_2 = 1$, 10, and 100) and H_2 (for H_2 mixing ratio varying from 10^{-6} to 10^{-1}) for solar UV $= 1$. Figures 3 and 4 give similar calculations for solar UV $= 10$ and 200, respectively. The important conclusion from these calculations is that in the prebiological early atmosphere, photochemical processes could not account for surface O_2 mixing ratios in excess of the parts per billion by volume level (ppbv $= 10^{-9}$). Hence, photochemical processes were not responsible for transforming the early atmosphere from a mildly reducing mixture to a strongly oxidizing mixture.

THE RISE OF OXYGEN AND OZONE

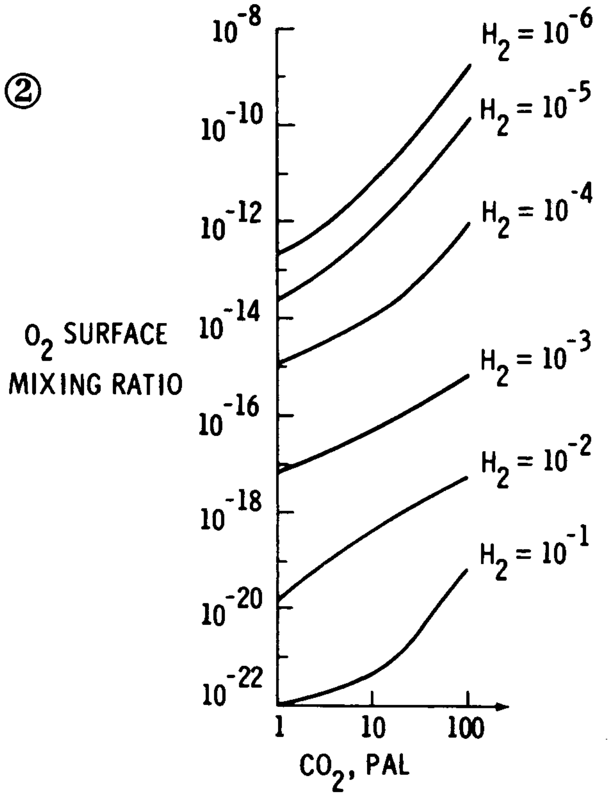
The calculations described in the previous section clearly indicate that photochemical processes were not responsible for transforming the atmosphere from a mildly reducing mixture to a strongly oxidizing mixture. The production of O_2 as a by-product of photosynthetic activity was the overwhelming source of atmospheric oxygen. The production of oxygen as a result of photosynthesis may be represented as

$$(8) \quad nH_2O + mCO_2 \xrightarrow{\text{chlorophyll}} C_m(H_2O)_n + mO_2$$

TABLE 4. The evolution of atmospheric oxygen (*Cloud*, 1983).

Time	Oxygen Level (% of present level)
2 b.y. ago	1%
1 b.y. ago	5%
670 m.y. ago	7%
550 m.y. ago	10%
400 m.y. ago	100%

②



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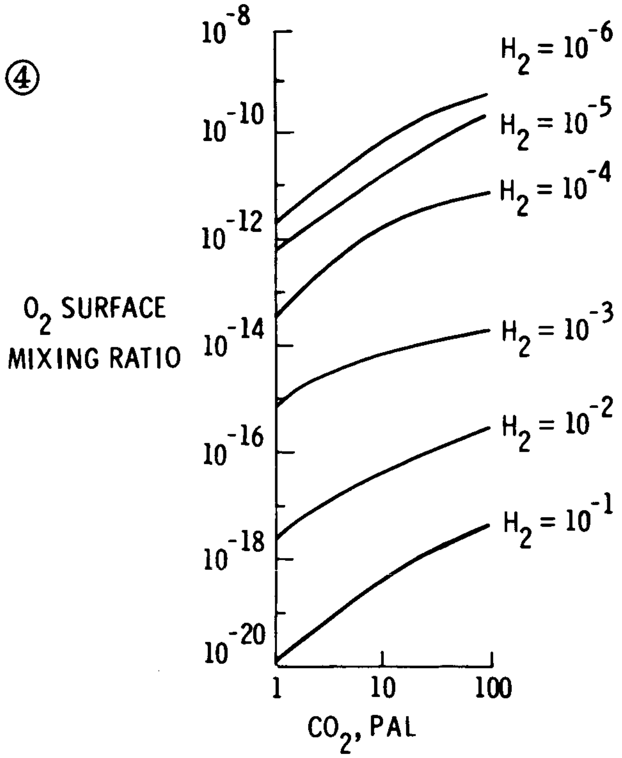
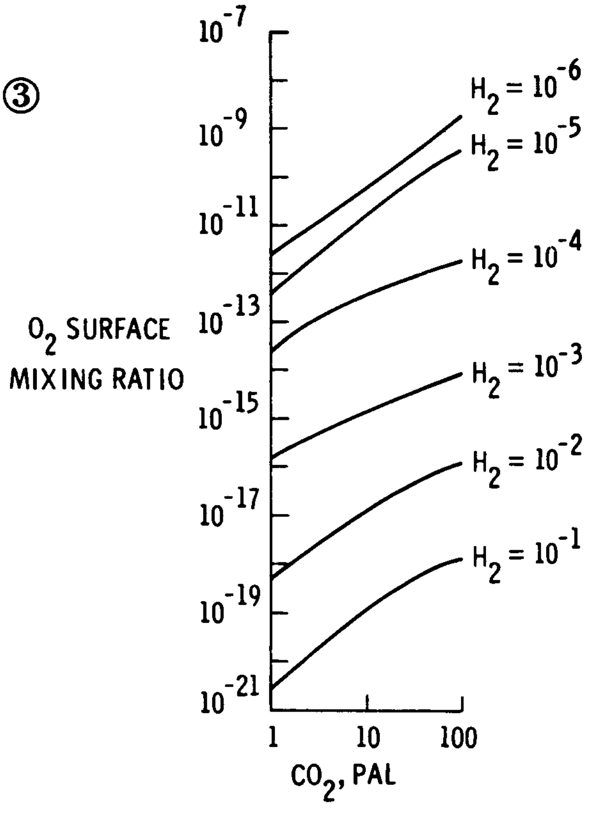


Figs. 2-4. Variation of surface O_2 mixing ratio as a function of CO_2 and H_2 for solar ultraviolet (UV) of 1 (Fig. 2), 10 (Fig. 3), and 100 (Fig. 4) (*Levine*, 1985b).

③



A possible timetable for the rise of atmospheric oxygen is summarized in Table 4 (*Cloud*, 1983).

The sources, sinks, and transfer rates of oxygen in the present atmosphere are summarized in Table 5. If all photosynthetic activity, the overwhelming source of atmospheric oxygen, were to cease, respiration and decay would continue to consume atmospheric oxygen. In the absence of photosynthesis, organic carbon (responsible for oxygen consumption via respiration and decay) would no longer be added to the reservoirs of surface organics. In the absence of photosynthetic production, the reservoir of surface organic carbon would be completely exhausted after about 20 years, at which time the amount of oxygen in the atmosphere would have decreased by less than 1% (*Walker*, 1977). With no carbon left in the surface organic reservoir, the burial of organic carbon in sediments would cease, but weathering would continue. It would take approximately 4 m.y. for weathering to consume all of the oxygen in the atmosphere (*Walker*, 1977).

As a result of photosynthetic activity, O_2 became a major constituent of that atmosphere. Accompanying and directly controlled by the buildup of O_2 was the evolution of O_3, which is formed photochemically from O_2. The photochem-

TABLE 5. Rates of oxygen production, destruction, and transfer (*Walker*, 1977).

1. *Production*	
Photosynthesis	10^{16}
Photolysis of water/escape of hydrogen	7×10^{9}
2. *Destruction*	
Respiration and decay	10^{16}
Combustion of fossil fuels	3×10^{14}
Weathering of sedimentary rocks	10^{13}
Reaction with volcanic hydrogen	5×10^{10}
3. *Transfer*	
Burial of surface organic matter to sedimentary rocks	10^{13}

Measurements in units of moles O_2/year; the atmosphere contains 3.8×10^{19} moles O_2.

ical production of O_3 was initiated by the photolysis of O_2 (reaction (9)), followed by the three-body recombination of O, O_2, and M (reaction (10))

$$(9) \qquad O_2 + h\nu \rightarrow O + O, \lambda \leq 242 \text{ nm}$$

$$(10) \qquad O + O_2 + M \rightarrow O_3 + M$$

There are a number of photochemical and chemical processes that lead to the destruction of O_3, including

$$(11)\ O_3 + h\nu \rightarrow O + O_2, \lambda \leq 1100 \text{ nm, and}$$

$$(12) \qquad O_3 + O \rightarrow 2O_2$$

In addition, O_3 is chemically destroyed through a series of catalytic cycles involving the oxides of nitrogen (nitric oxide, NO; and nitrogen dioxide, NO_2), hydrogen (hydroxyl, OH; and hydroperoxyl radical, HO_2), and chlorine (atomic chlorine, *Cl*; and chlorine oxide, *Cl*). Sources of nitrogen oxides in the early atmosphere included atmospheric lightning, biogenic production, and the oxidation of nitrous oxide (N_2O). The oxides of hydrogen were produced photochemically and chemically from water vapor. Volcanic emissions and sea salt spray were sources of chlorine in the early atmosphere. The catalytic cycles leading to the chemical destruction of O_3 are summarized here

$$(13) \qquad O_3 + NO \rightarrow NO_2 + O_2$$

$$(14) \qquad \frac{NO_2 + O \rightarrow NO + O_2}{\text{Net cycle: } O_3 + O \rightarrow 2O_2}$$

$$(15) \qquad O_3 + OH \rightarrow HO_2 + O_2$$

$$(16) \qquad \frac{HO_2 + O_3 \rightarrow OH + 2O_2}{\text{Net cycle: } 2O_3 + O \rightarrow 3O_2}$$

$$(17) \qquad O_3 + \mathit{Cl} \rightarrow \mathit{Cl}O + O_2$$

$$(18) \qquad \frac{\mathit{Cl}O + O \rightarrow \mathit{Cl} + O_2}{\text{Net cycle: } O_3 + O \rightarrow 2O_2}$$

We have investigated the origin and evolution of atmospheric O_3 as a function of the buildup of O_2 by solving reactions (9) to (18) for O_3. The results of these calculations are given in Fig. 5, where the vertical profiles of O_3 with and without the inclusion of chlorine species chemistry are given in terms of present atmospheric level (P.A.L.) of O_2, ranging from 10^{-4} P.A.L. to the present atmospheric level (1 P.A.L.).

The absorption of solar UV radiation is controlled by the total atmospheric burden or column density of O_3 corresponding to the five O_3 profiles shown in Fig. 5 is given in Table 6. It has been suggested that biological shielding of the Earth's surface was achieved when the total atmospheric burden of O_3 reached about 6×10^{18} O_3 molec. cm^{-2} (*Berkner and Marshall*, 1965), which is approximately half of the total O_3 burden in the present atmosphere. According to the calculations presented in Table 6, this atmospheric burden of O_3 was reached when O_2 reached 10^{-1} P.A.L.

Once atmospheric oxygen reached about 10% of its present atmospheric level, our calculations indicate that there was sufficient ozone in the atmosphere to shield the surface from biologically lethal solar ultraviolet radiation (200–300 nm). At this point in the Earth's history, life could leave the safety of the ocean and go ashore for the first time. The land, shielded from solar ultraviolet radiation for the first time, provided a major new niche for life. Once on land, life "exploded" both in numbers and diversification.

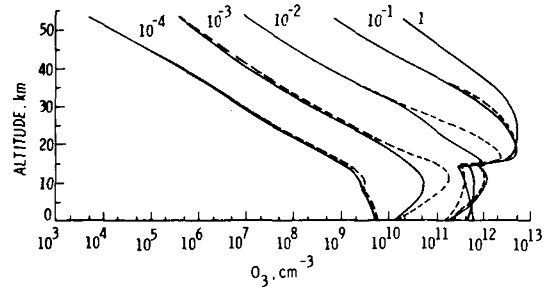


Fig. 5. Vertical distribution of ozone (O_3) with (straight lines) and without (dashed lines) the inclusion of chlorine species chemistry, as a function of O_2 level (in terms of present atmospheric level, P.A.L.) (*Levine*, 1982).

VENUS

Venus has been described as the Earth's twin because of its similar mass (0.81 Earth masses), radius (0.95 Earth radii), mean density (95% that of Earth), and gravity (90% that of Earth). However, in terms of atmospheric structure and chemical composition, Venus is anything but a twin of Earth. The mean planetary surface temperature of Venus is about 750K, compared to about 300K for Earth; the surface pressure on Venus is about 90 atmospheres, compared to 1 atmosphere for Earth; carbon dioxide at 96% by volume is the overwhelming constituent in the atmosphere of Venus, while it is only a trace constituent in the Earth's atmosphere (0.034% by volume). In addition, Venus does not have an ocean or a biosphere, and is completely covered by thick clouds, probably composed of sulfuric acid. hence, the atmosphere is inhospitable and very unlike the Earth's atmosphere (*Prinn*, 1985).

The clouds on Venus are thick and contain no holes; hence, we have never directly observed the surface of Venus from Earth. These clouds resemble a stratified low-density haze extending from about 45 to about 65 km. The total extinction optical depth of the clouds in visible light is about 29. The extinction of visible light is due almost totally to scattering. The lower clouds are found between 45–50 km; the middle clouds from 50–55 km; and the upper clouds from 55–65 km. The tops of the upper clouds, which are the ones visible from Earth, appear to be composed of concentrated sulfuric acid droplets.

As already noted, carbon dioxide at 96% by volume is the overwhelming constituent of the atmosphere of Venus. The next most abundant atmospheric gas is molecular nitrogen at 4% by volume. The relative proportion by volume of carbon dioxide and molecular nitrogen in the atmospheres of Venus and Mars are almost identical. The chemical composition of the atmosphere of Venus is summarized in Table 7. At the surface of Venus, the partial pressure of carbon dioxide is about 90 bars, molecular nitrogen is about 3.2 bars, and water vapor is only about 0.01 bar (more about water on Venus later). For comparison, if the Earth were heated to the surface temperature of Venus (about 750K), we would have a massive atmosphere composed of water vapor at a surface partial pressure of about 300 bars (resulting from the evaporation of the ocean), a carbon dioxide partial pressure of about 55 bars (resulting from the thermal composition of crustal carbonates), and a molecular nitrogen pressure of about 1–3 bars (resulting from the present atmosphere plus the outgassing of crustal nitrogen).

TABLE 6. Evolution of ozone as a function of increasing oxygen levels (*Levine*, 1982).

O_2 Level (PAL)	O_3 Column Density (cm^{-2})	Height of O_3 Peak (km)	O_3 Density at Peak (cm^{-3})
Without chlorine-species chemistry			
1	9.93 (18)*	20.5	5.53 (12)
10^{-1}	6.07 (18)	19	4.57 (12)
10^{-2}	2.47 (18)	16	2.48 (12)
10^{-3}	1.88 (17)	11.5	1.92 (11)
10^{-4}	5.58 (15)	0	5.63 (09)
Without chlorine-species chemistry			
1	9.70 (18)	20.5	5.40 (12)
10^{-1}	5.94 (18)	19	4.62 (12)
10^{-2}	1.59 (18)	10	1.16 (12)
10^{-3}	6.98 (16)	9	5.72 (10)
10^{-4}	5.18 (15)	0	5.42 (09)

*9.93 (18) = 9.93×10^{18}.

TABLE 7. Composition of the atmosphere of Venus (*Lewis and Prinn*, 1984).

Gas	Volume mixing ratio Troposphere (below clouds)	Volume mixing ratio Stratosphere (above clouds)
CO_2	9.6×10^{-1}	9.6×10^{-1}
N_2	4×10^{-2}	4×10^{-2}
H_2O	10^{-4}–10^{-3}	10^{-6}–10^{-5}
CO	$(2-3) \times 10^{-5}$	5×10^{-5}–10^{-3}
HCl	$<10^{-5}$	10^{-6}
HF	?	
SO_2	1.5×10^{-4}	5×10^{-8}–8×10^{-7}
S_3	$\sim10^{-10}$*	?
H_2S	$(1-3) \times 10^{-6}$*	?
COS	$<2 \times 10^{-6}$	?
O_2	$(2-4) \times 10^{-5}$*	$<10^{-6}$*
H_2	?*	2×10^{-5}
^{4}Hc	10^{-5}	10^{-5}
^{20,22}Ne	$(5-13) \times 10^{-6}$	$(5-13) \times 10^{-6}$
^{36,38,40}Al	$(5-12) \times 10^{-5}$	$(5-12) \times 10^{-5}$
^{84}Kr	$<2 \times 10^{-8}$–4×10^{-7}	$<2 \times 10^{-8}$–4×10^{-7}

*Single experiment; corroboration required.

A major puzzle concerning the chemical composition of the atmosphere of Venus (as well as the atmosphere of Mars) is the stability of carbon dioxide and the very low atmosphere (above 100 km), carbon dioxide is readily photodissociated with a photochemical atmospheric lifetime of only about one week. The recombination of carbon monoxide and atomic oxygen in the presence of a third body to reform carbon dioxide is only efficient at higher atmospheric pressures occurring at and below 100 km. However, at these lower altitudes, atomic oxygen recombines with itself in the presence of a third body to form molecular oxygen considerably faster than the three-body reaction that leads to the recombination of carbon dioxide. Thus, essentially all of the photolyzed carbon atmospheric concentrations of carbon monoxide (CO) and oxygen [atomic (O) and molecular], the photodissociation products of carbon dioxide. In the daytime upper dioxide produces carbon monoxide and molecular oxygen. Yet, the observed upper limit atmospheric concentration of molecular oxygen above the cloud tops could be produced in only about one day, and the observed abundance of carbon monoxide could be produced in only about three months. Photodissociation could easily convert the entire concentration of carbon dioxide in the atmosphere to carbon monoxide and molecular oxygen in only about 4 m.y., geologically a short time period. This dilemma also applies to carbon dioxide on Mars. Considerable research has centered around the recombination of carbon monoxide and molecular oxygen back to carbon dioxide. It became apparent that the only way to maintain low carbon monoxide and oxygen concentrations and high carbon dioxide concentrations in the 100–150 km region is by the rapid downward transport of carbon monoxide and oxygen, balanced by the upward transport of carbon dioxide. It is believed that carbon dioxide is reformed from carbon monoxide and oxygen at an altitude of about 70 km through various chemical reactions and catalytic cycles involving chemically active trace compounds of hydrogen and chlorine.

If Venus and the Earth contained comparable levels of volatiles and outgassed them at comparable rates, then Venus must have somehow lost about 300 bars of water vapor. This may have been accomplished by the "runaway greenhouse." In a runaway greenhouse, outgassed water vapor and carbon dioxide on Venus entered the atmosphere and thus contributed to a steadily increasing atmospheric opacity and increasing surface and atmospheric temperatures. On Earth, water vapor condensed out of the atmosphere forming the ocean, and the oceans then removed atmospheric carbon dioxide via dissolution and subsequent incorporation into carbonates. The greater proximity of Venus to the sun and its higher initial surface temperature appears to be the simple explanation for the divergent fates of water vapor and carbon dioxide on Venus and Earth. In the runaway greenhouse scenario, the photodissociation of massive amounts of outgassed water vapor in the atmosphere of Venus would have led to the production of large amounts of hydrogen and oxygen. Hydrogen could have gravitationally escaped from Venus, and oxygen could have reacted with crustal material. The runaway greenhouse and the accompanying high surface and atmospheric temperatures, too hot for the condensation of outgassed water on Venus, would explain the present water vapor-deficient and carbon dioxide-rich atmosphere of Venus. An alternative suggestion is that Venus may have originally accreted without the levels of water that the Earth contained, resulting in a much drier Venus.

MARS

The atmosphere of Mars is very thin (mean surface pressure of only about 6.36 mbars), cold (mean surface temperature about 220K with the temperature varying from about 290K in the southern summer to about 150K in the polar winter), and cloud-free, making the surface of Mars readily visible from the Earth. As already noted, the composition by volume percentage of the atmosphere of Mars is comparable to that of Venus. Carbon dioxide is the overwhelming constituent (95.3% by volume), with smaller amounts of molecular nitrogen (2.7%) and argon (1.6%) and trace amounts of molecular oxygen (0.13%) and carbon monoxide (0.08%), resulting from the photodissociation of carbon dioxide (the composition of the atmosphere of Mars is summarized in Table 8). Water vapor and ozone (O_3) are also present, although their abundances vary with season and latitude. The annual sublimation and

TABLE 8. Composition of the atmosphere of Mars (*Lewis and Prinn*, 1984).

Species	Abundance (mole fraction)
CO_2	0.953
N_2	0.027
^{40}Ar	0.016
O_2	0.13%
CO	0.08%
	0.27%
H_2O	(0.03%)*
Ne	2.5 ppm
^{36}Ar	0.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	(0.03 ppm)*
	(0.003 ppm)*

Species	Upper limit (ppm)
H_2S	<400
C_2H_2, HCN, PH_3, etc.	50
N_2O	18
C_2H_4, CS_2, C_2H_6, etc.	6
CH_4	3.7
N_2O_4	3.3
SF_6, SiF_4, etc.	1.0
HCOOH	0.9
CH_2O	0.7
NO	0.7
COS	0.6
SO_2	0.5
C_3O_2	0.4
NH_3	0.4
NO_2	0.2
HCl	0.1
NO_2	0.1

*Very variable.

precipitation of carbon dioxide out of and into the polar cap produce a planet-wide pressure change of 2.4 mbars, or 37% of the mean atmospheric pressure of 6.36 mbars.

The amount and location of water vapor in the atmosphere of Mars are controlled by the temperature of the surface and the atmosphere. The northern polar cap is a source of water vapor during the northern summer. The surface of Mars is also a source of water vapor depending on the location and season. The total amount of water vapor in the atmosphere varies seasonally between the equivalent of 1 and 2 km^3 of liquid water, with a maximum occurring in the northern summer and the minimum in the northern winter. Ozone is present only when the atmosphere is cold and dry (*Barth*, 1985).

There is evidence to suggest that significant quantities of outgassed carbon dioxide and water vapor may reside on the surface and in the subsurface of Mars. In addition to the polar caps, which contain large concentrations of frozen carbon dioxide and, in the case of northern polar cap, frozen water, there may be considerable quantities of these gases physically absorbed to the surface and subsurface material. It has been estimated that if the equilibrium temperature of the winter polar cap would increase from its present value of about 150K to 160K, sublimation of frozen carbon dioxide would increase the atmospheric pressure to more than 50 mbars. This in turn would cause more water vapor to leave the polar cap and enter the atmosphere. Mariner and Viking photographs indicate the existence of channels widely distributed over the Martian surface. These photographs show runoff channels, tributary networks, and streamlined islands, all very suggestive of widespread fluid erosion. Yet there is no evidence for the existence of liquid water on the surface of Mars today. In addition, a significant quantity of water vapor may have escaped from Mars in the form of hydrogen and oxygen atoms, resulting from the photolysis of water vapor in the atmosphere of Mars. If the present gravitational escape rate of atoms of hydrogen and oxygen has been operating over the history of Mars, then an amount of liquid water covering the entire planet about 2.5 m high may have escaped from Mars. Viking measurements of argon and neon in the atmosphere of Mars suggest that Mars may have formed with a lower volatile content than either Earth or Venus. This is consistent with ideas concerning the capture and incorporation of volatiles in accreting material, and how volatile incorporation varies with temperature, which is a function of the distance of the accreting terrestrial planets from the sun.

Unlike the very thick atmosphere of Venus, where the photolysis of carbon dioxide only occurs in the upper atmosphere (above 100 km), the photodissociation of carbon dioxide on Mars occurs throughout the entire atmosphere, right down to the surface. For comparison, the 6.36 mbar surface pressure of the atmosphere of Mars corresponds to an atmospheric pressure at an altitude of about 33 km in the Earth's atmosphere. On Mars, carbon dioxide is reformed from its photodissociation products, carbon monoxide, and oxygen by reaction involving atomic hydrogen (H) and the oxides of hydrogen.

Viking photographs indicate that the surface rocks on Mars resemble basalt lava. The red color of the surface is probably due to oxidized iron. The soil is fine-grain and cohesive, like firm sand or soil on Earth. Viking experiments indicated that there is no evidence for organic molecules or for biological activity in the Martian soil, despite unusual chemical reactions produced by the soil and measured by the life detection experiments.

THE OUTER PLANETS

Jupiter, Saturn, Uranus, and Neptune are giant gas planets—great globes of dense gas, mostly molecular hydrogen and helium, with smaller amounts of methane, ammonia, water vapor, and various hydrocarbons produced from the photochemical and chemical reactions of these gases. They formed in the cooler parts of the primoridal solar nebula, so gases and ices were preserved. These gas giants have ring systems and numerous satellites orbiting them. As already noted, the outer planets are more massive, larger, and have very dense atmospheres that contain thick clouds and aerosal and haze layers. The solid surfaces of the outer planets have never been observed, and we have only observed the top of the cloud and haze layers. In many ways, Jupiter and Saturn are a matched pair, as are Uranus and Neptune. Jupiter and Saturn appear to have cores of silicate rocks and other heavy compounds comprising about 25 Earth masses, surrounded by thick atmospheres of molecular hydrogen and helium. The total mass of Jupiter and Saturn are 318 and 95 Earth masses, respectively. Uranus and Neptune appear to possess much less massive hydrogen/helium atmospheres relative to their cores. The total mass of Uranus and Neptune are only 14.5 and 17 Earth masses, respectively. The large satellites of Jupiter, Saturn, and Neptune are all larger than the Earth's moon with several comparable to the size of Mercury. One of these satellites, Titan, the largest satellite of Saturn, has an appreciable atmosphere.

The Voyager spacecraft obtained high resolution images of Jupiter, Saturn, and Uranus, their rings, and satellites. Voyager instrumentation gathered new information on the chemical composition of their atmospheres. The helium abundance in the atmosphere of Jupiter was found to be 11% by volume (with molecular hydrogen at 89% by volume), very close to that of the sun. The presence of methane, ammonia, water vapor, ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), benzene (C_6H_6), phosphine (PH_3), hydrogen cyanide (HCN), and germanium tetrahydride (GeH_4) in the atmosphere of Jupiter was confirmed (see Table 9). The magnetosphere of Jupiter was found to be the largest object in the solar system, about 15 million km across (10 times the diameter of the sun). In addition to hydrogen ions, the magnetosphere was found to contain ions of oxygen and sulfur. A much denser region of ions was found in a torus surrounding the orbit of Jupiter's satellite, Io. The Io torus emits intense ultraviolet radiation and also generates aurora at high latitudes on Jupiter. In addition to a Jovian aurora, huge lightning flashes and meteors were photographed by Voyager on the nightside of Jupiter. A thin ring surrounding Jupiter, much narrower than Saturn's, was discovered by Voyager. The four large "Galilean" satellites, Ganymede, Callisto, Europa, and Io, were studied in detail. Io was found to have at least 10 active volcanoes. Sulfur resulting from the Io's volcanic emissions is responsible for the orange color of its surface, as well as the presence of sulfur dioxide in its atmosphere (at a partial pressure of only about one ten millionth of a bar). Io's volcanic emissions are also responsible for the ions of oxygen and sulfur in Jupiter's magnetosphere.

After encountering Jupiter and its satellites, both Voyager spacecraft visited Saturn and its satellite system. The six previous known rings were found to be actually composed of innumerable, individual ringlets with very few gaps observed anywhere in the ring system. Complex dynamical effects were photographed in the ring system, including spiral density waves similar to those believed to generate spiral structure on galaxies. The helium content of the atmosphere of Saturn was found to be about 6% by volume (with molecular hydrogen at about 94% by volume), compared to about 11% for Jupiter. The trace gases in the atmosphere of Jupiter include methane, acetylene, ethane, phosphene, and propane (C_3H_8) (see Table 10).

Titan, the largest satellite of Saturn, was found to have a diameter slightly smaller than Jupiter's largest satellite, Ganymede. The atmosphere of Titan is covered by clouds and layers of aerosols and haze, and has a surface pressure of about 1.5 bars, which makes it about 50% more massive than the Earth's atmosphere. The surface temperature of Titan is a cold 100K. Titan's atmosphere is mostly molecular nitrogen, with smaller amounts of methane and trace amounts of carbon monoxide, carbon dioxide, and various hydrocarbons (see Table 11 for the chemical composition of Titan in different regions of its atmosphere). The surface of Titan may hold a large accumulation of liquid methane.

After encountering Saturn, Voyager 2 was targeted for Uranus. On January 24, 1986, Voyager 2 had its closest approach to Uranus. As Voyager approached Uranus, its

TABLE 9. Composition of the atmosphere of Jupiter (*Strobel*, 1985).

Constituent	Volume mixing ratio*
H_2	0.89
He	0.11
CH_4	0.00175
C_2H_2	0.02 ppm
C_2H_4	7 ppb
C_2H_6	5 ppm
CH_3C_2H†	2.5 ppb
C_6H_6†	2 ppb
CH_3D	0.35 ppm
NH_3	180 ppm
PH_3	0.6 ppm
H_2O‡	1–30 ppm
GeH_4	0.7 ppb
CO	1–10 ppb
HCN	2 ppb

*ppm ≡ parts per million; ppb ≡ parts per billion.
†Tentative identification, polar region.
‡Value at 1 to 4 bars.

TABLE 10. Composition of the atmosphere of Saturn (*Strobel*, 1985).

Constituent	Volume mixing ratio
H_2	0.94
He	0.06
CH_4	0.0045
C_2H_2	0.11 ppm
C_2H_6	4.8 ppm
CH_3C_2H*	No estimate
C_3H_8*	No estimate
CH_3D	0.23 ppm
PH_3	2 ppm

*Tentative identification.

TABLE 11. Composition of the atmosphere of Titan (*Strobel*, 1985).

Constituent	Volume mixing ratio		
N_2		0.76–0.98*	
	Surface	*Stratosphere*	*Thermosphere (3900 km)*
CH_4	0.02–0.08	≤0.026	0.08 ± 0.03
Ar	<0.16		<0.06
Ne	<0.002		<0.01
CO	60 ppm		<0.05
H_2	0.002 ± 0.001		
C_2H_6		20 ppm	
C_3H_8		1–5 ppm	
C_2H_2		3 ppm	~0.0015 (3400 km)
C_2H_4		0.4 ppm	
HCN		0.2 ppm	<0.0005 (3500 km)
C_2N_2		0.01–0.1 ppm	
HC_3N		0.01–0.1 ppm	
C_4H_2		0.01–0.1 ppm	
CH_3C_2H		0.03 ppm	
CO_2		1–5 ppb	

*Preferred value.

cameras indicated that Uranus did not exhibit the colorful and very turbulent cloud structure of Jupiter or the more subdued cloud banding and blending of Saturn. The very low contrast face of Uranus exhibited virtually no detail. The atmosphere of Uranus, like those of Jupiter and Saturn, is composed primarily of molecular hydrogen (about 85%) and helium (15 ± 5%). Methane is present in the upper atmosphere and is also frozen out in the form of ice in the cloud layer. The methane in the upper atmosphere selectively absorbs the red portion of the spectrum and gives Uranus its blue-green appearance. The volume percentage of methane may be as low as 2% deep in the atmosphere. Acetylene (C_2H_2) with a mixing ratio of about 2×10^{-7} was also detected in the atmosphere of Uranus. The temperature of the atmosphere was found to drop to a minimum of about 52K (at the 100 mbar pressure level) before increasing to about 750K in the extreme upper atmosphere.

After its encounter with Uranus in January, 1986, Voyager 2 was targeted for an encounter with Neptune in September, 1989. After its encounter with Neptune, Voyager 2 will join Voyager 1 and Pioneer 10 and 11 and escape the gravitational pull of the sun and head for the stars.

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ORAL PRESENTATION

REMARKS ON THE CONFERENCE

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About ten years ago, there appeared above me, about eight feet in the air, a face without any body connected to it. The lips moved but the face otherwise was expressionless. It said: "So you want to learn how the world began. Very well, then, I will tell you. But remember, you fool, no one asked you to take this journey!" This took place in King's Dominion Park, near Richmond, which used to be called an amusement park. I guess they call them theme parks nowadays. This reminded me that there is something funny about this field: if not as risky as this dire spectre seemed to make it, perhaps it was somewhat strange.

I think that this feeling is shared by a lot of people. It always seemed to me to be rather odd that this should be the case. I think we all know that questions concerning the origin of the Earth and the origin of the solar system, creation science, or whatever you want to call it, have been a major subject of human thought for centuries. We know that with relatively little trouble we can get our names in *Science* and *The New York Times* by publishing something on this subject, so the public in general tends to regard this as a very important and exciting field to work in. Nevertheless, it is not a field chosen by many scientists.

One might ask why this is so. I think there is a general feeling that people who work on these things are biting off too much, they're trying to solve problems that are premature, that are not ready for solution and that there is not really all that much hope of doing something worthwhile, as compared for example to doing some of the more ordinary things that fill up volumes and volumes of the *Journal of Geophysical Research* and the *Journal of the Chemical Society*. I think there is something to this. On the other hand, I am also encouraged by the fact that there have been developments in the last decade or so that are working in the direction of changing our field of science—the origin of the solar system—into a more normal type of science, which is not simply pursued by eccentric, elderly gentlemen who fight with one another's theories of the origin of the solar system, and cause much amusement. I think we are actually in the process (although we may not realize it) of developing this science into what I would regard as a more normal kind of science wherein one can undertake finite tasks and receive rewards in the form of an audience and perhaps even employment.

A development that has been to a large extent responsible for this is what I consider, in some general way, the fact that we are developing the broad outlines of what one may call a standard model. We do not have a consensus by any means, but we are developing a sort of standard model of solar system formation, which of course has many bifurcations and branch points and mainly poses questions rather than gives answers. Some people would call this a "paradigm," but I think this term, if it has any meaning at all, has meaning only in retrospect, not in the real time advance of science. It is my hope, and possibly even expectation, that this could lead to a community of people that, although not always agreeing with one another (heaven forbid they should), may nevertheless have shared understandings.

Their discussions would take the form not so much as "my theory of solar system origin" versus "your theory of solar system origin," but instead instill a feeling that there exist relatively well-defined observational, experimental, and theoretical problems that need to be studied in a disciplined way if we are to make progress. A further advantage of such an intellectual environment would be to give substance to individual efforts, and would make it worthwhile to devote one's energies to pursuit of what would generally be considered to be an obscure problem were it not for the fact that there will be people around who will be interested in the results.

For example, consider Alan Boss' and Hiroshi Mizuno's study of whether or not planetesimals would be expected to disrupt as they go by a planet, or Al Cameron and Willy Benz's work on what would happen if an object comparable to the size of Mercury were to hit that planet. In isolation these things seem somewhat esoteric and obscure, but in the context of a program to investigate what one might call a standard model for the origin of the solar system, they are very important. Of course it might be said that there is danger of prematurely establishing a dogma and there could be something to that. On the other hand, I don't think that this is a clear and present danger in this field.

To a large extent what we have heard today from the various speakers was an outline of the standard model, which starts with a molecular cloud, leading to a disk, and subsequently to star formation. At every step along the way important questions are raised. Even at this early stage, in addition to the problems associated with how the star itself forms, there is the important question as to whether or not and the extent to which gravitational instabilities occur in the gas disk. There is the question of the formation of the residual solar nebula, the formation of grains in that nebula, and the formation of planetesimals from those grains. In one version of the standard model, this would be followed by runaway growth of planetesimals, at least beyond a "snow line" at 5 A.U. leading to the rapid formation of Jupiter.

In my mind the central question in planet formation is this formation of Jupiter, which is the key to everything. We have been flitting around and making some progress with terrestrial planets, meteorites, and other things. But every question we've been working on in recent years always boils down to how Jupiter is formed. This is a very important matter: how Jupiter can form on a short time scale. Perhaps, as Hayashi says, Jupiter did not form on a short time scale; perhaps it took a hundred million years. I find very serious problems with that alternative. It seems to me the problem of how to form Jupiter in a million years or less, perhaps a few hundred thousand years, is a very important matter to pursue. I see the most attractive possibility for doing it at the present time as a runaway in that region, but of course that is just arm-waving at this point. How that really proceeds, perhaps through Ganymedian puff balls of Stevenson or by various other means, remains to be determined. Every step along this path is a serious problem that deserves to be followed.

There is also the point I mentioned earlier this afternoon: If Jupiter forms by a runaway on a short time scale, the question arises as to why a runaway did not occur in the asteroid belt. If a runaway occurred in the asteroid belt, one would expect Earth-sized objects to grow in the belt on more or less the same time scale. The matter of removing these objects from the asteroid belt is a formidable one. So, one could study the various ways in which the incipient formation of Jupiter, or other causes that one might suggest, could inhibit a runaway. This might depend on fundamental differences in the physical properties of planetesimals, e.g., the differences between snowy planetesimals and rocky planetesimals.

In the terrestrial planet region, with or without runaway, a case can be made that an excess of large planetesimals may be formed. The fate of these bodies would either be to be isolated out at the ends like Mercury or Mars, or else to impact the large terrestrial planets, Earth and Venus, with all the possible consequences of giant impacts: lunar origin, the removal of atmospheres, and possibly effects on Mercury's composition. These problems have been studied only in a very rudimentary way.

There are also specific questions that form a link between dynamics and geochemistry. If the asteroid belt did not undergo a runaway at the time Jupiter formed, the largest bodies in the belt can be calculated to be $\sim 10^{23}$ to 10^{24} grams, comparable in size to the present asteroid belt. If they were then pumped up to eccentricities comparable to their present eccentricities, would they grind themselves down to look like the present asteroid belt? Preliminary calculations by Chapman and Davis suggest that this may indeed be the case. If so, where does all this material go? Again, the problem has not really been worked, but rough estimates indicate that 6×10^{25} grams of the material would land on both Mars and the Earth. This would represent 1% of the mass of the Earth and 10% of the mass of Mars and might lead to a reasonable explanation for the chemical differences of these two bodies.

The point of these remarks is not to propose answers but to point out that at every point along the way, the standard model can help one pose reasonably well defined physics, chemistry, and observational problems that can be addressed at this stage. If there were some common understanding that this whole chain of events is worth studying, regardless of whether or not one believes in giant gaseous protoplanets or runaways or whatever, controversies would have a substantive framework—other battles of personality—in which to be centered. I think we are getting to that point. I am encouraged that this is happening. Much of the recent work, much of the material we heard at this meeting, are the kind of things we would not have heard about at all 20 years ago.

Another important development that became clear from the talks today is that the field of solar system origin is increasingly becoming an observational science. The recent developments in infrared astronomy, radio astronomy, and millimeter radio astronomy allow the identification of objects in the galaxy that may well serve as models for the origin of our own solar system. One may look to the future for more exciting developments, including the search for other solar systems.

The study of meteorites can also be considered an observational science. It is important that the study of meteorites be placed in its proper context, that it becomes a cornerstone of planetary science. In this connection, it is important to recognize that meteorites are not simply samples of the solar nebula. In fact, meteorites are rocks broken off of outcrops in recent times—they come from real places in the present solar system. In the view of most people, meteorites come from the asteroid belt. This is a real place, unlike the solar nebula, which we will never visit and always will remain some magic kingdom that we like to talk about and hope to understand. Asteroids are a different thing; they are right there and we could go there, like Las Vegas or Philadelphia, if we only had the fare. We can observe them through telescopes and study real dynamic problems such as how meteorites come from asteroids, how asteroids fragment to make Apollo objects, and how this material comes to Earth. It is important that this point be in the minds of those who work on meteorites, because the contrasting history between the asteroid belt and its neighbor Jupiter is central to our understanding of the formation of the solar system.

Meteorites bear a record that they have been through a very tranquil thermal environment. They have been physically broken up, but still preserve relicts of their origin in the solar nebula. This is clearly telling us something about the way in which one region of the solar system evolved, as contrasted to the region beyond it, where the giant planets formed. The conditions also differ from the very high temperature events that occurred in the terrestrial planet region. Everything we've been telling NASA about primitive bodies being the clue to the origin of the solar system is probably true. In this general program of trying to understand the formation of the solar system, the observation and study of these bodies—not just the meteorites, but the bodies themselves, the asteroids and comets—is central to these investigations.

I think we have a great opportunity; there is a lot of work for everybody. Everybody doesn't have to have a theory for the origin of the solar system. There are well-defined problems that are relevant to anybody's theory of the origin of the solar system. We might justifiably hope for a great leap forward, but if not, the rewards of the long march may be equally great.

DISCUSSION

MIKE DRAKE: There are several things George has said that I think we should talk about. First, why is it that you feel that Jupiter must form fast; why couldn't it form at the same rate as everything else and just take a little longer to grow? What observational evidence is there that it formed fast?

WETHERILL: Jupiter must have formed while there was still gas around, so if Jupiter took a hundred million years to form, there would still be gas around during this time. This means that the Earth would have formed in the presence of full nebular gas and all the implications of Hayashi's 10^{26} gram atmosphere must be faced. I am not ruling this out, but I think that there are serious geochemical difficulties associated with having a full complement of solar nebula volatiles present on the Earth and its atmosphere during the time the Earth formed. There is a question of how to get rid of this material. Perhaps if we have enough outflow it can be done. Arguments have been given by various workers about how to remove this atmosphere, but it is not clear they will work. By the time we get to hundred million year time scales, this resolution of geochronological methods I spoke of starts to become a serious matter. I think that this whole question is a legitimate line of investigation. The idea that Jupiter formed first and removed material from the asteroid belt on an appropriate time scale is a more attractive alternative.

DRAKE: All it means is that it formed before the asteroid belt *per se*, or at least the seeds got growing faster. It doesn't mean that it formed any faster than the main terrestrial planets—is that a fair statement?

WETHERILL: The real problem, which several people have mentioned this afternoon, is that if you go about calculating the formation of Jupiter in the classical "Safronov" way it takes $>10^8$ years. Most people find this unsatisfactory and so there is an effort to determine whether this result is true. I think there is a good chance the answer is "no." This is a problem that has not been completely pursued but there are several people working on it and it is beginning to look like Jupiter may have formed on a time scale that was short compared to the time scale of terrestrial planet formation of $\sim 10^7$ or 10^8 years. This is sufficiently short that the asteroid belt could be truncated at an early stage in its growth, rather than proceeding to full size, which it would do in a hundred million years. It's a question of trying to put together an internally consistent story with a quantitative basis. I gave an outline of a particular story. If you are telling the Kyoto story, you must do a similar thing, and I invite you to do so.

DRAKE: Let me proceed with one of the things that I am not sure is supported by serious observational evidence. There is a part of the "standard model" where there must have been giant impacts.

WETHERILL: Perhaps I did not express myself properly. What I said was that the outline of the standard model was the whole series of talks we had this afternoon. I went through it briefly indicating some steps along the way (including some clearly indicated as private opinions) that represent bifurcations and branch points. My point is that there exists a whole class of problems, including these bifurcations and branch points, that I can work on regardless of whether I belong to the Kyoto school or not. I think it was perfectly legitimate for Mizuno and I to have co-authored a paper on the consequences of the Earth having a 10^{26}-gram atmosphere, without having to defend a theory of solar system origin that produces such an atmosphere. One can imagine a tree that starts with a molecular cloud and goes up through various branches. The entire framework and branch points define questions that are legitimate objects for study in themselves.

I did not say that giant impacts were a necessary consequence of the standard model. If you form planets from planetesimals, which is not necessarily the way it happened, although I personally strongly prefer it, then the question is: How do the planetesimals accumulate into planets? I have worked out some ways of doing this that lead to giant impacts. I have not been successful in finding any way of making planets from planetesimals without having extra-large bodies. That doesn't mean that it is impossible, by any means. But the problem is posed in the standard model: If, for example, you started with 10 km planetesimals, how would you expect these to evolve into planets? That's the problem. You might get an answer that does not involve giant impacts when you work on the problem.

We're all working on the same big problem. We should appreciate one another's work. I am not saying "my theory is the standard model and yours isn't."

DRAKE: I absolutely agree with what you said. The point I was trying to communicate was that to my knowledge, there is in fact no basis to the statement that there will be a relatively violent inner solar system with giant impacts as a natural outcome of theoretical studies, unless the initial conditions of these studies presuppose the outcome. I think you would concede me the point that we know sufficiently little about how grains agglomerate to make centimeter-size objects, which in turn agglomerate to make kilometer-size objects, and so on. Therefore, we don't actually know, for example, that the initial conditions that go into calculations that lead to the prediction of giant impacts are actually correct.

WETHERILL: In all of these things you have to do what we used to do in the olden days, back in 1984. We called it "double-thinking." You cannot pursue these problems without taking them very seriously, even though when you get all done someone will legitimately ask: How do you know you're really right?

At the same time I think it is a mistake to say, well, all you do is assume different initial conditions and you get different results. I don't think that is really true. I start with 10-km planetesimals and try to understand the best I can how these evolve. They're going to evolve into large objects and I can then try to understand how these large objects accumulate and collide with one another. Giant impacts involving high velocities and high temperatures would be involved in the process. This is quite different from what we see in the asteroid belt. I can pursue this seriously and I take it seriously when I finish. Of course, if grains cannot form planetesimals, then there is no way to make planets out of planetesimals. Formation of planetesimals from grains is a separate and very important problem, the serious study of which is essential.

I would be extremely interested if somebody were to start with 10-km planetesimals and in a similar way show how, without any large impacts, nothing but four large planets would grow out of nothing but very small bodies. I have thought very hard about how to do that and I have failed to do so. I welcome somebody else doing it and I would be very interested in following their work. I am not in any way putting it down. On the other hand, I don't think it would be right for me to say that all I have to do is change this parameter in my computer program and I'll get a nice peaceful terrestrial planet formation. If you are going to say that the terrestrial planets formed in a way that did not involve high temperatures, melting of the planets during their formation, or burial of heat by impacts during their formation, up to and including impacts large enough to make the Moon, then there is a job to show how that can be done. It is not just a matter of twiddling a parameter.

JILL TARTER: The actual title of this workshop is "The Origins, plural, of Solar Systems, plural." Your summary dealt with the origin of this solar system. Is there really any sense in talking about the study of the search for other solar systems? We sell to NASA that concept, but is it anything more than lip service? Is there much to be learned about the issues we are discussing here from the study of other solar systems, assuming we can find them in some stage of their formation or evolution?

WETHERILL: I personally think that the formation of our solar system involves many stochastic events. If the terrestrial planets formed by accumulation of planetesimals with material of similar surface density to that we see at the present time, the fact that we have four planets rather than forty is probably no coincidence, no accident. On the other hand, I would say that the fact that the Earth is bigger than Venus is an accident (in the sense that one speaks of being sure in this business). There are all kinds of possible variations—there could be five terrestrial planets, Venus could be bigger than the Earth, and so on. It is quite possible that the timing of the removal of the solar nebula governs whether the Earth would have a Hayashi type atmosphere. I wouldn't be at all surprised if Hayashi is totally wrong about our solar system and we look out and find a Hayashi solar system somewhere. One outcome of the study of theory, as I see it, is that we are living on one of many possible solar systems. There are stochastic and chaotic effects that determine whether we have this or that kind of solar system. The main interest I have in searching for other solar systems is to get away from the nagging feeling that perhaps this whole thing really is foolish. If the formation of solar systems is so improbable that it only happens once in a galaxy, then the hope of being able to calculate from first principles how this extremely rare event took place is groundless. If we found one other solar system, the statistics of one would be pretty good (we have statistics of zero right now—the fact that we are living in one doesn't mean anything because if we weren't here we wouldn't be studying the problem). If we found one more, then I would guess that the event is pretty common. If we found 10 and then 50 and started to observe the variations among these, then we could address questions like whether Bode's Law is of deep significance, which I doubt. We would start to see the whole variety of solar systems—comparative cosmogony. This would be a major advance not only of our understanding of our solar system, but of the universe in general.

DAVID BLACK: I agree with what you have said. Studying why the Earth is bigger than Venus may be an interesting exercise, but it misses the broad brush issues. Until we find other solar systems we should try to study the broad issues appropriate to our own solar system. For example, why is Jupiter where it is and as big as it is? These are the only issues that are broad brush for our solar system that we can now address.

TARTER: There is no way to make sure that we will find the number of solar systems that equals the number of different models that we have to describe them.

WETHERILL: Hopefully there are some general principles that we are admittedly groping for.

BLACK: If we search in 10, 12, or 20 nearby G2 stars and we can't find any with a planet the size of Jupiter, I would say fundamentally we have learned something very important.

AL CAMERON: I would like to raise a point of political science, i.e., whether we really should be calling this the origins of solar systems, plural. One of the points George was making is that we have gone from an idiosyncratic field to being one that is semirespectable. The whole SETI relationship is one that has not achieved the same image of respectability, regardless of what we may think about that. Therefore, to the extent that this is to become a new program that will be given some public visibility, my own recommendation would be to call it "The Origin of the Solar System" and regard the search for other solar systems as an intrinsic part of that.

WETHERILL: That is a matter of tactics that I am not an expert on.

STU WEIDENSCHILLING: To reply to Mike Drake's point, I don't regard this as a search for appropriate initial conditions, but rather a search for relevant processes. Unless we get the total physics of the problem correct and we say that we understand what processes are relevant in forming the solar system, it is going to be useless to say we just change the initial conditions and use imperfect models that ignore some phenomenon that really was important in forming the solar system. We are not going to learn anything from that. We might even produce a model that, given some set of conditions, seems to produce an acceptable solar system. If we stop at that point and convince ourselves that we have solved the problem, then we are going to be in serious trouble. Sooner or later somebody will discover a better piece of physics that has been overlooked. In the decade or so since I got interested in this problem there are a couple of phenomena that have entered into our consciousness that were not there when I started. I don't know whether these are of overwhelming importance or not, but these are things such as convective instability in the accretion disk that weren't mentioned 10 years ago; tidal torques that vary between protoplanets and the disk weren't even suspected 10 years ago. It is not yet clear if these are of great importance in forming the solar system, but it is highly presumptuous of us at this point to say we have all the phenomena we need and that if we can just find the right permutation of these with the right initial conditions, that gives us a solar system. We have to do a lot more basic thinking on the fundamentals.

WETHERILL: I agree. I would also like to add a remark. Suppose Stu had attempted to work on convective instability in a gas disk in the absence of a context, what I would call a standard model. Hardly anybody would pay attention. It is important that we create an environment (and we are in the process of doing this) in which when someone works on a problem of that sort, and I gave several other examples, there exists a community that agrees that the problem is worth working on and wonders what the answer is, regardless of whether they belong to the Moscow school, Kyoto school, Tucson school, or whatever. That is the important point I was trying to make, not whether giant impacts are necessary.

DRAKE: I have no disagreement with what you just said.

WEIDENSCHILLING: Certainly the formation of Jupiter is important, especially from a mass weighed basis. One might also say that perhaps the formation of Neptune is a key in the sense that we might be able to find an apparently acceptable way of forming Jupiter on reasonable time scales, yet if that kind of model still leaves us with Neptune taking 10^{10} years or more to form then this doesn't do us a whole lot of good. If we can find a way to form Neptune in an acceptable time, that might change our picture of how Jupiter formed as well.

WETHERILL: Understanding how the Earth formed is actually even helping us to understand how Jupiter formed. My hunch is that if we get Jupiter and Saturn, Uranus and Neptune will somehow fall into place, but that could be overly optimistic.

PAUL WARREN: Something that troubles me very much, and I don't hear anyone proposing how to solve this problem, is: At what stage does accretion get to before the nebula gets dissipated? Maybe this is something observations can help us with. The two statements that you made—Jupiter probably accreted in much less than 10^8 years and Jupiter accreted while there was still gas around—suggest that accretion got pretty far. I trust you dynamical people very much to be unprejudiced about how you get your conclusions except that I'm a little wary that you might pick initial conditions that are tractable or amenable to your particular Monte Carlo calculations.

WETHERILL: Several speakers outlined the problem of trying to make Jupiter in less than 10^8 years. I am hopeful that there are some ways to do this that are promising.

WARREN: The weakest link in your "standard model" is, when did the gas dissipate? I don't hear anybody talking about how to solve this problem.

WETHERILL: Actually there has been quite a bit of discussion of this, particularly in connection with observations of pre-main-sequence stars. But certainly no definitive answer is available at present. The point I was making, however, is that it should not be necessary for people, including myself, who are working on the origin of the solar system to feel they are a failure because they cannot explain every single question that is asked about the origin of the solar system. We should be able to work on well-defined physics problems—convective instability, tidal disruption of planetesimals—and say, "Here, I've done a piece of work that is worthy of respect and that is part of this whole story. I don't have to tell you when the gas was removed if I don't know when the gas was removed."

GEORGE BOWEN: Isn't it true that the gas need not have been and probably was not dissipated at the same time everywhere in the solar system?

WETHERILL: That is an interesting question. When the T-Tauri outflow starts blowing, my feeling has always been that it is going to blow it all away. It is not going to leave it all sitting out in Jupiter and leave the terrestrial region clean. On the other hand, maybe that's how it happened. When people ask how you know that you don't have a full complement of nebula gas at Jupiter and none at the Earth, well I've never worked on that problem, because it didn't sound right to me. I might well have been wrong about that.

JOE NUTH: In the outflow models talked about for the bipolar nebulae, the actual size of the hole in the disk was on the order of a couple of AU in the later stages of the bipolar outflow. So there may actually be differential outflow.

DRAKE: Let's accept for the moment that Jupiter forms very fast and hence exists as the second most massive object in the solar system outside of the sun, prior to the assembly of the terrestrial planets. To my knowledge, no simulation of planetesimal accumulation has been conducted with considerations of Jupiter or the asteroid belt being present. Would you feel that having something as massive as Jupiter in your simulation, if you could model it, might affect the outcome?

WETHERILL: As far as the terrestrial planets are concerned, Jupiter at the present time causes eccentricities of about 0.02 (in the terrestrial planet region). During the later stages of terrestrial planet formation, the calculations I have made indicate that the planetesimals accelerate themselves to eccentricities as high as 0.3; so Jupiter should be relatively unimportant at that point. During the early stages of accumulation the question of whether or not you get a runaway depends critically on whether or not the eccentricities are low or very low. If during the first 100,000 years of terrestrial planet formation a proto-Jupiter could cause significant eccentricities, in spite of having gas present and the tendency of secular perturbations to be in phase with each other, this could be a critical factor that turns a runaway into a nonrunaway. My guess would be that this is more likely to be important in the asteroid belt than in the terrestrial planet region. If Jupiter eventually pumped the asteroid belt up to 0.15, it would have to pump it up to 10^{-3} first. Jupiter perturbations could be the key to whether or not runaways occur in some parts of the inner solar system. That is part of the reason why I say that, whatever we work on, we ultimately get back to how, why, and when Jupiter formed.

BLACK: If you increase the eccentricity of Jupiter just a little bit it disturbs the hell out of the inner solar system. You have to increase the mass by a factor of 10 to keep the eccentricity the same. If Jupiter had an eccentricity of 3 or 4 times the present eccentricity, and it stayed that way, it would destroy the inner solar system.

WETHERILL: I didn't know that.

Section II: Joint Working Group Reports

REPORT OF THE JOINT WORKING GROUP ON INTERSTELLAR CHEMISTRY AND PRIMITIVE BODIES IN THE SOLAR SYSTEM

There are many areas of research in which the interests of astronomers studying interstellar chemistry overlap those of meteoriticists conducting analytical studies. A major question of fundamental importance to both communities is, "How homogeneous was the material in the molecular cloud from which the solar system formed?" A corollary might be "How close to equilibrium did matter within the cloud come at any particular stage of the collapse?" On the grand scale of the entire solar system, it is fairly clear that the material in the cloud was both well-mixed and relatively homogeneous: variations within solar-system objects such as planets, moons, asteroids, and comets can generally be ascribed to processes operating during and after the collapse of the nebula rather than to preexisting heterogeneities. However, recent microanalytical studies of meteorites and interplanetary dust particles clearly show some rather striking heterogeneities on very small scales: e.g., on the order of single grains and grain aggregates. Some of these isotopically unusual materials can be attributed to specific sites of production, e.g., within the outflows of red giants, novae, or supernovae. Certain other materials were probably produced by gas-grain chemistry within the molecular cloud itself prior to the collapse of the solar nebula. In either case, it is clear that complete equilibrium and thorough homogenization of all preexisting material was not attained within the solar nebula. This opens up the exciting possibility of studying preserved interstellar and even circumstellar materials in the laboratory for comparison with astronomical observations of those regions. Similarly, the preservation of rather delicate interstellar and circumstellar features within certain classes of "primitive objects" can place limits on the temperatures and/or pressures experienced by such objects during their formation, provided that laboratory data on the rates of gas/solid or solid/solid "homogenization reactions" are obtained.

The recommendations of this working group can be divided into two general areas. The first involves astronomical observations that could clarify the composition and structure of molecular clouds today, so as to understand better the probable boundary conditions that should be used to constrain evolutionary models of the solar nebula based on meteoritic observations. The second involves specific meteoritic observations, which may be able to constrain the variety of astrophysical processes operating within the giant molecular cloud just prior to the formation of the solar system. The development of both theoretical models and laboratory data sets are integral parts of both recommended areas of study and are discussed as appropriate.

High spectral and spatial resolution observations of the infrared emission and absorption features of dust components in giant molecular clouds are needed. These could be used to constrain the degree of crystallinity of the bulk silicate, ice, and carbonaceous components of the dust, based on laboratory spectra of individual meteoritic constituents and on laboratory-produced analogs of such materials. Furthermore, such measurements could be used to understand the degree of association of specific organic and silicate grain components. In this regard it should be possible to infer the distribution of specific refractory grain components (such as SiC, MgS, CaS, and carbonaceous grains) as they form in circumstellar outflows and are transported and modified throughout the giant molecular clouds. This would require high spectral resolution in order to carry out chemically specific searches for the spectroscopic signatures of such tracers and high spatial resolution to constrain the overall degree of heterogeneity of the solid grain components and thus the degree of internal mixing in the cloud.

Ground-based infrared telescopes operating in the atmospheric windows can yield spatial resolutions of ~0.5" (75 A.U. at the distance of the Taurus cloud complex) and a spectral resolving power of 10^3. Airborne observations can provide spatial resolutions of a few arc seconds and spectral resolution approaching 10^5 over much of the 25- to 300-micron wavelength range. Space-based infrared facilities will eventually provide increased sensitivity, access to the entire spectral region from 1 to 1000 microns with subarcsecond spatial resolution, and resolving power in excess of 10^3 at the shorter wavelength.

Grain alteration and destruction may also be studied using millimeter arrays to trace discrete changes in gas phase components (such as SiO) that may be associated with the sputtering and destruction of grains. Observations at 1-mm wavelength should be able to map clouds with a spatial resolution of 0.5" and a spectral resolution in excess of

10^6, more than sufficient to follow the gas emission features in velocity.

Meteoritic observations suggest that regions of enhanced O/H ratios may have been produced in the accretion shock bounding the solar nebula by infall and partial vaporization of up to centimeter-size grains. Arguments based upon the maximum possible efficiency with which matter can attenuate light preclude the existence of large numbers of "macroscopic" grains (larger than a few millimeters) having a compact structure, if our measurements of the general interstellar extinction and of the cosmic abundance of the elements are correct. However, no one yet knows for certain the type of structure that might form in a giant molecular cloud if a "normal" distribution of interstellar grains coagulates. It has been suggested that such an aggregate may be a "fractal" where grain-grain contact is minimal, and long-range electromagnetic interaction between grains is effectively eliminated. Would such an aggregate have a distinctive electromagnetic signature at some wavelength in the observable spectrum? What would this signature be, and in what region of the spectrum? Theoretical calculations of the scattering of fractal aggregates could be valuable, as could microwave analog measurements of models of such grains. Synthesis of organic and inorganic fractal aggregates might be studied under microgravity conditions. Measurement of the light scattering and absorption properties of these fractal aggregates could provide answers to some of these questions. If a distinctive signature for such particle aggregates is predicted or observed in a simulation, then careful astronomical searches for such aggregates should be made in various environments, e.g., circumstellar shells or collapsing cloud cores. Detection of these aggregates would significantly affect models of mixing within interstellar clouds and of accretion and dust settling within the solar nebula.

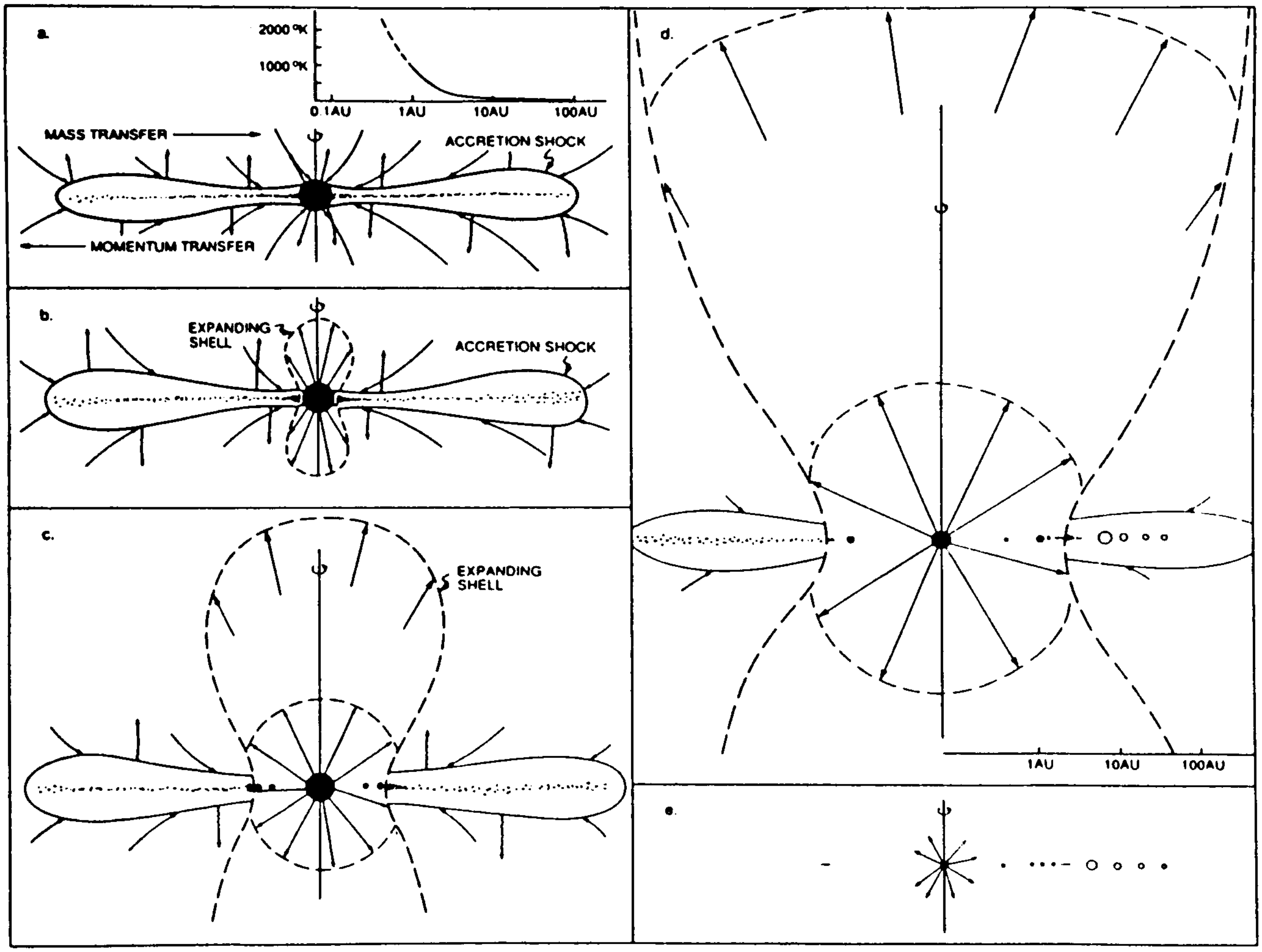
Even though the solar system is to a very large degree isotopically homogeneous, some meteoritic measurements of isotopically anomalous abundances in elements such as carbon, nitrogen, oxygen, and hydrogen have been suggested to result, in part, from chemical processes that occurred in the molecular cloud prior to the collapse of the solar nebula. Careful astronomical studies should be undertaken in order to measure the degree of chemical and isotopic heterogeneity both between and within giant molecular clouds and cloud cores. Detailed theoretical models of such regions could be tested against these observations, especially with regard to possible correlated isotopic partitioning in specific grain reservoirs. These observations and models could then be used to predict distinctive isotopic signatures for specific components that might be identifiable in primitive meteorites, interplanetary dust particles (IDPs), and comets. The degree to which such distinct material is lost from a particular sample might serve as an indication that a specific level of processing had occurred at some stage in the formation of that meteorite type. Therefore, advanced microanalytical capabilities need to be directed toward the molecular, elemental, isotopic, and structural characterization of various meteoritic components on a grain-by-grain basis.

In this same area, meteoritic studies have already produced evidence that distinct circumstellar materials have survived passage through the interstellar medium, inclusion into the solar nebula, and incorporation into meteorite parent bodies. As examples, isotopic measurements have shown that ^{50}Ti and ^{48}Ca components from a distinctive neutron-rich, equilibrium burning process are widespread in meteorites. Studies of rare inclusions in carbonaceous chondrites have revealed details of the way in which r-, s-, and p-process nuclides were introduced into the early solar system. Similarly, analyses of carbonaceous carriers of noble-gas components have shown that they were generated in various astrophysical sites such as supernovae and red giant branch stars. The magnitude and actual number of the nucleosynthetic reservoirs implied by such observations are unknown, and thus it is not known how much homogenization occurs within the interstellar medium or the degree of mixing and scale of turbulence present in the primitive solar nebula. Thorough studies of the distribution of such anomalies among primitive meteorite components might be used to ascertain the length scale of these mixing processes.

Gamma-ray observations of the decay of ^{26}Al in the interstellar medium have greatly modified the interpretation of previous measurements of ^{26}Mg anomalies attributable to extinct ^{26}Al in certain refractory meteoritic components. The meteoritic measurements had been interpreted as the signature of a supernova "triggering" the collapse that formed the nebula. Whether or not the quantities of live ^{26}Al in the modern interstellar medium are adequate to explain the meteoritic data is not yet clear, nor is it known whether the ^{26}Al entered the protosolar system live or as the ^{26}Mg daughter product. The possible presence of ^{26}Al in the primitive nebula—especially in moon-sized and smaller bodies—is a crucial piece of information (in addition to accretional or impact heating) needed to model the thermal history of planetesimals in the early solar system. Therefore, relatively high spatial resolution gamma-ray maps of the ^{26}Al distribution in the modern interstellar medium, with special emphasis on the degree of variation around the average concentration, are important in order to establish limits on the possible concentration of live ^{26}Al that may have been present in forming planetesimals. Present limitations on the resolution of gamma-ray observations may allow measurements of ^{26}Al abundances on a cloud-to-cloud basis. Such measurements will indicate whether or not abundance variations of the order of a factor of 5 or more are commonplace, and therefore will indicate whether the overabundance of ^{26}Al inferred for certain meteorites (a factor of 5 higher than in the interstellar medium) is a significant constraint.

Astronomical observations have suggested that several distinct types of refractory grains are produced in separate environments. These grains might yet be stored in fairly pristine condition in the icy cores of comets. Structural, morphological, and isotopic characterization of interplanetary dust particles and samples returned from the nucleus of a comet might lead to identification of individual grains that are attributable to particular astrophysical environments, e.g., SiC grains showing high ^{28}Si and ^{13}C probably formed in the atmosphere of a carbon-rich star. If such grains are found, then detailed characterization of the petrographic context would be warranted. It would be important to determine if the grains were coated with an organic residue. It would also be useful to determine the crystal structures and morphologies of particles and particle aggregates as clues with which to determine the mechanism by which those grains nucleated and grew. If a sufficient sample of individual grains are identified, it may be possible to test whether the relative abundances of particular size grains follows any of the proposed size distributions for interstellar dust.

A final area where a significant amount of work is needed is in the evaluation of the role of nonequilibrium chemical processes in both astronomical and nebular settings. This area could have a major impact on our understanding of the composition of stellar outflows, the importance of ion-molecule reactions and sputtering in molecular clouds, and the structure of organic molecules in the early solar nebula. It is clear that thermodynamic equilibrium models are inadequate to treat such systems, yet relevant kinetic data are not available to construct more realistic, process-oriented models. As examples, rate constants for many nonthermal neutral-neutral reactions are unknown, as are the mechanisms for many radical-neutral and ion-molecule reactions. Very little is known about possible gas-grain interactions. Such reactions are the postulated source for H_2 in the interstellar medium (by default) and are proposed as catalysts for the formation of organic molecules in the solar nebula, yet relevant rate information is virtually nonexistent. A proper kinetic model of relevant processes must be developed to interpret astronomical observations of the temperature-density-composition profiles in molecular clouds (e.g., why don't the complex molecules condense on the grains?). This model might then be extended to observations of disks around young stars to explain the variation of particular molecular species (such as SO or SO_2) as a function of the strength of local shocks or the temperature and pressure profile of the disk. Nonequilibrium chemistry is also likely to have played a significant role in the evolving solar nebula. However, many of the signatures of nonequilibrium chemistry can be obscured by subsequent processing. Observation of distinct instances of predictable nonequilibrium chemistry in astrophysical environments would serve as a validation of the theory, which could then be applied to processes in the protosolar nebula.



Schematic representation of five stages in the history of the early solar system. (**a**) Cross-sectional view of the protostar/accretion-disk geometry of the collapse phase. Infalling matter strikes the accretion disk at supersonic velocity and is decelerated at a shock. Matter within the disk moves toward the protostar while angular momentum is transferred outward. Heat is radiated perpendicular to the plane of the disk. An estimate of the temperature profile in the disk is shown (note logarithmic length scale). (**b**) Onset of early-pre-main-sequence-phase mass loss. The hot supersonic gas ejected from the protostar sweeps surrounding matter into a dense shell. The "bubble" of hot gas expands more rapidly in the directions of least resistance, perpendicular to the accretion disk. (**c**) The expanding "bubble" takes on a bipolar geometry. Intense protostellar mass loss is probably episodic, but the shell continues to expand during quiescent periods, driven by the momentum of previously ejected gas. During each stellar eruption, a dense ring of dust and gas forms at the leading edge of the accretion disk. After each eruption, the dust within each ring coagulates into larger masses that cannot be moved or destroyed by subsequent eruptions. (**d**) As accretion subsides, the energy supplied to the protostar and the intensity of stellar eruptions also decrease. Although the activity of the protostar is subsiding, the shell produced by the protostellar wind has become so large that the bipolar motion may be detected at vast distances. (**e**) T-Tauri stage: The intense stellar activity has subsided, the dust-and-gas cocoon has been dispersed, and the sun has contracted considerably. Both the inner planets and the gas giants may be well into the process of formation. From G. R. Huss, 1987, Ph.D. thesis, University of Minnesota.

C - 2

REPORT OF THE JOINT WORKING GROUP ON NEBULA MODELS AND ASTRONOMICAL OBSERVATIONS

The working group identified specific problem areas or major outstanding uncertainties in our current concept of the manner in which planetary systems form. These problem areas are: (1) the initial collapse of the nebula, (2) the onset of the growth of solid objects in the nebula and the accumulation of these solids into planetesimal-sized objects, and (3) interactions of the evolving sun with the solar nebula. A directed effort to focus the expertise of several diverse scientific disciplines on these problem areas could be extremely useful given our present level of understanding.

There are a number of well-established observations bearing on the general process of solar system formation. As an example, we know that stars often form in groups in the dense cores of giant molecular clouds. Flattened gas and dust disks are also observed in association with young stars; the radial extent of many of these disks is inferred to be comparable to the size of our own planetary system. Energetic "bipolar" flows are often observed aligned with the rotational axes of some of these disks. Young (10^5 to 10^7 years) solar-type stars are revealed, usually by the production of strong stellar winds. Disks have been observed around older main sequence stars. The best model for these disks is a flattened cloud of comets at an early stage of dynamical evolution accompanied by some additional solid debris. The largest members of these clouds may have masses comparable to Pluto.

The collapse and/or fragmentation of an interstellar cloud of gas and dust leads to the formation of flattened rotating nebulae or disks as well as to the central stars about which the disks rotate. Collapsing clouds, young stars, and circumstellar disks have all been observed in various evolutionary stages. Models of each stage of this evolution have been constructed. Unfortunately, neither the observations nor the models are of sufficient spatial resolution to tell us about many of the important details of the early stages of the solar nebula. The nature of this stage of the collapse process, as well as the consequences of dynamical processes (e.g., mass transfer into the sun) occurring within the disk-shaped nebula itself, must be much better constrained both observationally and theoretically.

We also need to know the distribution of single vs. multiple star systems and how the formation of pre-main-sequence single vs. multiple stars correlates with the initial conditions in the cloud. What role does multiple star formation play in the redistribution of angular momentum?

Both meteorites and interplanetary dust particles contain tangible evidence that places constraints on the small-scale accretion processes in the nebula that preceded the consolidation of material into planets. Evidence from these objects points to spatial and temporal variations in the reservoirs as well as to the nonequilibrium, transient chemical and thermal processing of materials. These processes are not addressed by current dynamical or chemical models of the nebula. The implications of these processes are significant and require much further study, both experimental and theoretical, before the full impact of inhomogeneity in the solar nebula is well understood. There are numerous important unanswered questions concerning different stages of our current view of the accretion of planetary-sized bodies. As an example, the structure and composition of the grains can greatly influence both the nebular opacity and the fraction of volatiles retained within growing planetesimals. We need to know the composition and structure of the interstellar grains in the precollapse molecular cloud as well as the results of the various metamorphic processes that may occur both during and after the onset of accretion.

The growth process, by which solid grains accumulated into comet/asteroid-sized objects and into the major planets, is poorly understood. The general consensus is that growth proceeded through several stages, each involving successively larger objects. However, many questions remain, such as the effect of nebular gas on the accretion process, the timing and effect of the T-Tauri wind vis-a-vis planet formation, and the degree of mixing between various planetesimal feeding zones within the nebula. Each of these questions may be addressed from both observational and theoretical perspectives.

Many questions concern the dynamics and structure of the disk itself as well as the disk's interaction with the protostar. For instance, do stars form from disks or vice versa? What determines the extent, mass, and energy budget of the disk? How are strong stellar winds generated and how do the winds interact with the material in the disk?

There are several lines of research that could produce significant results within the next decade. Seven examples of such projects recommended by this working group are detailed below.

1. High spatial and spectral resolution observations of star forming regions so that velocity distributions can be measured on scales of 10 A.U. or less. Ten to twenty A.U. resolution studies using millimeter interferometers and infrared cameras could be used to measure the extent, temperature structure, and possible asymmetries of protoplanetary disks. Binary companions to pre-main-sequence stars will be found with this high spatial resolution. Tenth parsec resolution studies of molecular cloud rotation properties could be used to examine the structure of the cloud.
2. High-sensitivity visible and infrared searches for objects that may be the largest members of a possible "inner" cloud of comets with orbits between about 50 and 100 A.U. in order to define the radial distribution of planetesimal material in our solar system.
3. A systematic deep survey of the swarms of asteroids trapped in the Jovian L4 and L5 libration regions. These poorly known swarms contain spectrophotometrically distinct objects that may have been derived from the outer part of the region in which terrestrial planets formed and that may therefore provide unique clues about the process of planetary accumulation.
4. High spatial resolution observations of the magnetic field strength and geometry in cloud cores and protostellar disks. Existing observations suggest that outflows from pre-main-sequence stars are aligned with ambient magnetic fields.
5. Further visible and infrared studies of those nearby mature stars, such as Beta Pictoris, which have recently been found to have extended dusty disks.
6. Numerical studies of the interaction of a strong stellar wind with a protoplanetary disk, carried out with sufficiently high resolution so that the models can be checked against high spatial resolution astronomical observations and theoretical scenarios for the removal of solar nebula gas from the terrestrial and giant planet regions.
7. Rigorous calculations of the three-dimensional collapse of dense interstellar clouds, through the formation of pre-main-sequence stars. Development of numerical algorithms capable of computing this evolution through both dynamical and quasi-equilibrium phases will be necessary to reach the basic theoretical goal.

In addition to near-term projects of the type discussed above, the working group also recommends support for several crucial flight projects that will ultimately be necessary for a full understanding of the early history of the solar nebula and the general problem of the origins of solar systems. The most important of these longer term projects are briefly discussed below.

Astrometric Telescope: The discovery of extrasolar planetary systems by astrometry or other techniques, followed by the detailed characterization of such systems, will add enormously to our present database, which now consists of only one instance of a known planetary system—our own.

Comet Rendezvous/Asteroid Flyby (CRAF) and Comet Nucleus Sample Return (CNSR) Missions: Comets are thought to contain the most pristine samples of the material that made up the primitive solar nebula. Careful examination of the morphology of the nucleus and of its major structural components, analysis of the bulk chemical and isotopic composition as a function of depth, and electron microscopy on individual dust grains that may be unaltered interstellar dust, can each provide a wealth of data not only on the initial nebular makeup and processing history, but also on the planetesimal accumulation process itself. These missions will open up an entirely new window on conditions in the early stages of star formation.

Space Infrared Telescope Facility (SIRTF): Careful, sensitive, infrared studies of cool prestellar objects and of the cometary clouds and particle disks around nearby stars can yield a significant database on the residual angular momentum and mass contained in these systems. The structure, density, and chemical composition of these disks could also yield clues to the processing history of that particular star's nebula, which could be compared to what is known of our own system's history.

Space IR/Millimeter Interferometer: Infrared and millimeter studies of protostellar clouds can yield a great deal of information about nebular processes, provided that the observations can be carried out at sufficiently high spatial and spectral resolution. Interferometric techniques at IR and millimeter wavelengths could potentially study motions of major gaseous and dust components in modern protoplanetary disks at spatial resolutions of less than 0.01 arc second. This would translate to a spatial resolution in the disk of less than an A.U. for the nearest protostellar regions.

Advanced X-ray Astronomy Facility (AXAF): This telescope will study the copious X-ray emission from the atmospheres of T-Tauri stars.

Stratospheric Observatory for Infrared Astronomy (SOFIA): This sensitive infrared telescope will have angular resolutions of a few arc seconds in the important middle infrared region, which is inaccessible from the ground. It will provide high sensitivity and modest angular resolution of the disks around nearby young stars.

REPORT OF THE JOINT WORKING GROUP ON SOLAR NEBULA MODELS AND METEORITES

Historically, the study of meteorites has had little influence on astrophysical models of the solar nebula, and such models have not strongly affected the interpretation of meteoritic data. The reasons for this paucity of interaction are complex, but are related at least in part to differences in scale. The major goal of nebular models is to explain the formation of the sun and planets, i.e., the overall configuration of the solar system. Chemistry is considered (if at all) in the context of gross trends of planetary bulk compositions. Meteorites, on the other hand, yield detailed information on chemical and isotopic compositions of small-scale, even microscopic, components with complex histories. These data do not fit easily into any simple unifying context, and are not predicted by the nebular models. Ultimately, the meteorite data and astronomical observations must constrain the models. The role of the models is to provide a context for interpretation of the data, and to suggest relevant experiments that may yield additional constraints.

There is a need to study aggregation and lithification processes by which presolar grains and nebular material became incorporated into asteroids and eventually meteorites. In particular, researchers need to be able to distinguish the properties of primary remnant presolar grains from those due to processing in the solar nebula and within planetesimals. Even if this is achieved, there remains the uncertainty as to where in the solar nebula these processes occurred. For example, the various types of asteroids may reflect different conditions within the confines of the present belt, or comprise material that formed over a larger or smaller range of heliocentric distance. Even if analysis of a meteorite could uniquely determine a set of conditions (e.g., pressure and temperature) under which its components accreted, it is likely that any model could match these conditions somewhere in the nebula. Thus, we need to quantify the processes that transported or mixed material within the nebula before and after the accretion of asteroid-sized bodies. The observed diversity of components within primitive meteorites can be used to constrain the effectiveness of these processes, and to relate them to models of the accretion and the collisional and thermal evolution of planetesimals. There is a need to construct nebular models on sufficiently fine spatial scales to predict, or at least allow, small-scale processes that may produce local regions with anomalous compositions and thermal properties. Such processes introduce a level of complexity and poorly constrained variables that are not warranted at our present level of understanding. However, if predictions or constraints concerning the extent, timescale, or degree of such processes arise naturally from a nebular model, then meteoritic data might be used to test various aspects of that model's predictions.

It is important to recognize that even primitive meteorites are mixtures of materials that have experienced complex histories, including residence within asteroidal parent bodies. As a result, the signatures of presolar or nebular processes are commonly overprinted by the effects of secondary processing, such as thermal annealing, shock metamorphism, and aqueous alteration.

The working group has identified a number of areas that have the potential of relating meteoritic properties to processes that occurred in the nebula. While studies in these areas might initially be done independently by either modelers or analytical meteoriticists, the goal is to build the necessary bridges between the two fields. Once the appropriate knowledge is obtained, e.g., a sound theoretical understanding of the processes involved and a solid analytical data base, then the properties of meteorites may be related directly to specific nebular models or processes. The areas recommended for study are grouped into three categories: (1) those primarily amenable to theoretical modeling; (2) those dependent on data obtainable by meteoriticists; and (3) those areas that can be studied in different ways by both communities.

THEORETICAL STUDIES

The primary goal of theoretical studies at this time is to improve understanding of fundamental physical processes, e.g., convection, turbulence, gravitational torques, etc., in order to identify those that are relevant to constructing realistic models of the solar nebula. These include, but are not limited to, the following:

What processes of angular momentum transport were effective in the nebular disk? Turbulent viscosity due to convection necessarily involves diffusive mixing of material over a range of heliocentric distances. Density waves, due to global instability modes, and magnetic fields, do not *require* (but may allow) such mixing. In recent years there has been significant improvement in theoretical understanding of convection in a differentially rotating disk, largely due to analytic studies. More work is needed, e.g., on criteria of temperature and opacity for the onset, maintenance, and decay of convection. Both convection and density waves are amenable to study by three-dimensional hydrodynamic simulations with modern supercomputers.

What is the nature of the dynamical interactions between solid particles and nebular gas? The drag force exerted by gas dominates the motions of solid particles in the disk in the size range roughly from micrometers to kilometers. Numerical modeling of particle aggregation has yielded some estimates of the timescales for settling and coagulation, and of the size distribution of aggregates, if efficient sticking is assumed. Much remains to be examined, e.g., the effect of varying degrees of turbulence in the disk. Analytic studies suggest that if settling produces a dense dust layer (spatial density greater than that of the gas) near the central plane, then shear between that layer and the surrounding gas will cause localized turbulence, accompanied by radial transport of gas and dust (both inward and outward). Detailed modeling of this process is possible with numerical fluid-dynamics codes and large computers. Both analytic and numerical studies are needed to constrain the nature of aerodynamic sorting of particles by size or density before or during the accretion of planetesimals; such information may aid in the interpretation of meteorite textures.

How did the asteroids form and evolve? It is not known whether the asteroids formed in their present locations, or if the main belt includes bodies that accreted elsewhere and were placed there by some process of orbital evolution. The present belt contains only a small fraction of a planetary mass; it is unclear when and how the "missing mass" was removed. Some fraction of this material presumably impacted the terrestrial planets, and may have had detectable effects on their compositions, especially their volatile inventories. Theoretical models of accretion, including the effects of perturbations by Jupiter, may clarify the degree and mechanism for the depletion of the primordial belt. There is also need for improved modeling of the subsequent collisional evolution of the asteroids, using laboratory-scale data on hypervelocity impacts and recent improvements in scaling laws, to understand the process of fragmentation. The pieces of asteroids delivered to Earth as meteorites do not provide an unbiased sample of the belt; some regions near resonances may be overrepresented, while others may not yield significant numbers of meteorites. The asteroidal sources of ordinary chondrites have not been identified with confidence, and may comprise only a modest fraction of the belt. A better understanding of the collisional evolution of asteroids and sources of meteorites might diminish the apparent need for nearly ubiquitous production of chondrules in the solar nebula.

METEORITIC STUDIES

The constituents of meteorites, within which is carried the record of early solar-system processes, may be conveniently divided into three categories based on their putative origins: presolar, nebular, and planetesimal, defined below. In practice, assignment to one or another of these categories is not always straightforward, but the distinctions are useful. For our purposes, it is important to match the theoretical issue being addressed with the appropriate category of meteoritic evidence, recognizing that the observational record is far from complete.

The record carried in presolar grains is discussed in the report of the Joint Working Group on Interstellar Chemistry and Primitive Bodies in the Solar System.

Nebular Material

We define nebular material as material that either condensed or was thoroughly reprocessed while dispersed in the solar nebula before the accumulation of planetesimals. Incorporation of such material into a meteorite may be manifested in either of two ways. Either the surviving nebular entity, e.g., a mineral grain or a lithic particle such as a chondrule or inclusion, is identified and picked out for detailed study, or the presence of one or more primitive nebular components is inferred from a bulk property of a meteorite, e.g., its content of refractory lithophile elements or radiogenic noble gases. Both approaches can be fruitful in defining nebular conditions and processes. Topics that may be addressed by one or another of these approaches, or by both, include the following.

Mixing of material between different nebular regions. Most primitive meteorites are breccias, i.e., disequilibrium mixtures of materials that probably formed at different heliocentric distances. The observed distribution of such distinguishable materials presumably carries information concerning the transport of particulate material between different regions of the solar nebula. Quantitative inventories of these mixtures within different meteorites are needed to constrain dynamical models of the transport processes.

Thermal history of the nebula. Many primitive meteorites include components that retain evidence of one or more episodes of high temperature, i.e., above about 1500°C. There are good reasons to believe that at least some of these episodes occurred while material was dispersed in the nebula prior to planetesimal accumulation. However, the spatial and temporal scales of such heating are unknown. For example, chondrules, which are common in most primitive meteorites, were clearly made by melting preexisting mineral grains in transient events of up to 1600°C, but it is not known whether those events were restricted to a narrow region of the nebula or whether they occurred throughout the inner solar system. Nonetheless, the spatial or temporal extent of such heating events must be accommodated in the thermal history of any nebular model if it is to be successful.

Chronology of different stages in nebular evolution. Formation of many meteorite constituents can be dated by one or more of a variety of radiometric schemes. In conjunction with petrologic and other information concerning the origins of those constituents, such data can be used to construct a chronology for nebular and planetesimal processes. For example, igneous differentiation and aqueous alteration both apparently took place in different parent bodies within about 10 m.y. of the formation of refractory inclusions in the nebula.

Recognition of a T-Tauri stage during solar evolution. A fundamental question with broad implications for solar-system history is whether or not the sun went through a highly active, i.e., T-Tauri, stage early in its history. Such an episode could be recorded by solar-flare tracks and spallogenic nuclides preserved in certain meteoritic mineral grains, and there is already significant evidence for such enhanced early activity. In principle, radiochronological analyses could be used to date the timing and duration of such a T-Tauri stage.

Prevalence and strength of nebular magnetic fields. Several components of primitive meteorites are characterized by remanent magnetizations apparently recording significant paleointensities in the nebula. Not only is the measurement of such fields of fundamental importance, but their magnitude could have had a major influence on the course of nebular evolution, i.e., they constitute important input parameters to nebular models.

Planetesimal Material

Although secondary processes on meteorite parent bodies may have obscured many aspects of presolar and nebular processes, these processes are of interest in their own right. Study of secondary materials can address the following topics.

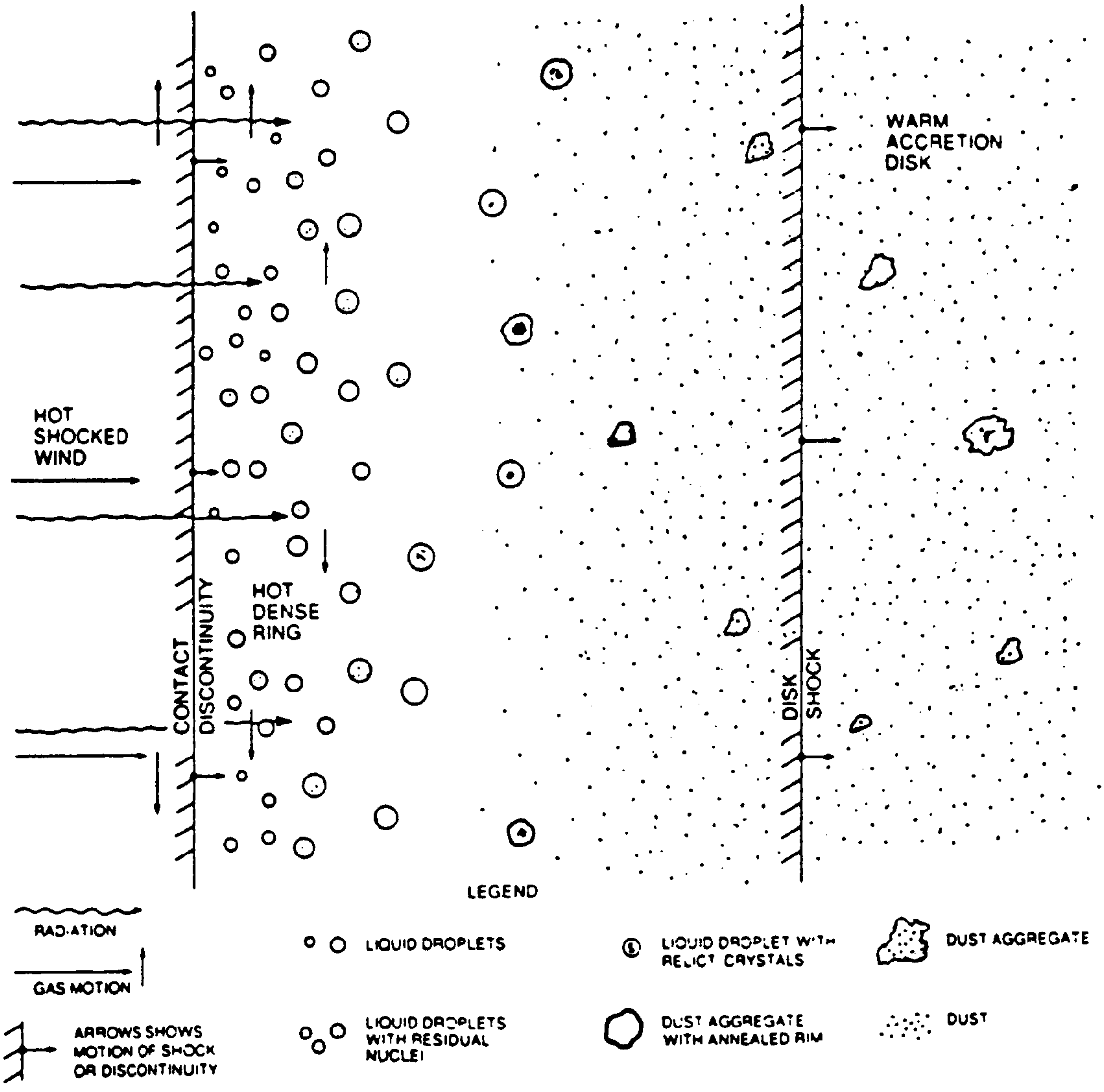
The nature of heat sources in solid objects in the early solar system. A fundamental issue in modeling the evolution of nebular material is the possible effect of heating by freshly synthesized ^{26}Al and/or electromagnetic induction in a T-Tauri solar wind. The continuing investigation of the distribution of ^{26}Mg anomalies due to ^{26}Al decay and of irradiation effects due to early solar activity is of immediate relevance to this issue. An equally important issue is the extent to which primitive bodies were heated during accretion or via impacts.

Defining the final stages of planetesimal accretion. Many meteoritic breccias record the impact history of objects very early in solar-system history. That impact environment represented the final stages of the collisional process that built up the asteroid-sized planetesimals, and study of the resulting breccias can clarify important details that need to be included in models of accretion in the nebula.

COMBINED INQUIRIES

What were the sources of opacity in the disk, and how would opacity vary with conditions in the nebula? Potential sources of opacity include presolar refractory grains, nebular condensates, ices, and photochemical smog. Extinction will depend on the abundances, compositions, and structures of particles (e.g., single grains, compact particle clusters, or fractal aggregates). Laboratory experiments are needed to determine the expected compositions and production rates of photochemical particulates. Formation of fractal aggregates and determination of their properties can be studied by laboratory experiments and by computer modeling of aggregation. Searches for fractal structures among interplanetary dust particles (IDPs) should be conducted. Eventually, microgravity experiments will be able to determine the efficiency of coagulation as a function of composition, temperature, and impact velocity. One major result of such studies should be improved interpretation of observations of protostellar disks. Estimates of gas/dust ratios depend on the size distribution, morphology, and crystal structure of the particles. Conversely, observations of such disks, if interpreted using plausible heavy-element abundances, may yield better constraints on the size distribution and state of particles during various stages of cloud collapse and disk evolution.

What are the nature and effects of small-scale (temporal or spatial) processes on nebular material? Settling to the central plane and radial transport of gas and/or grains across condensation boundaries (e.g., of H_2O ice) may produce localized zones of anomalous composition in the nebula. These processes need to be modeled quantitatively to estimate the spatial extent, lifetimes, and degree of deviation from cosmic abundances. Laboratory measurements are needed for rate constants of gas/grain chemical reactions such as hydration/dehydration, oxidation, isotopic equilibration, etc. Analyses of meteorites, including interplanetary dust particles, should be conducted to determine evidence for such processes that may have occurred in the nebula rather than on a parent body. Analyses should also be conducted to determine the nature and extent of putative compositionally anomalous regions.



A schematic blowup of a dense ring produced at the leading edge of the accretion disk by early-pre-main-sequence protostellar eruptions. Gently processed disk material (right) is further heated by one or more weak disk shocks, and then is incorporated into a dense ring as the disk is eroded. Intense radiation from the eruptive early-pre-main-sequence protosun heats the inner portion of the ring, evaporating fine dust and melting and later evaporating dust aggregates. Hot gases are lost perpendicular to the disk plane through thermal motion. When an eruption ends, liquid droplets crystallize to form chondrules. From G. R. Huss, 1987, Ph.D. thesis, University of Minnesota.

REPORT OF THE JOINT WORKING GROUP ON PLANETARY ACCUMULATION AND EVOLUTION

A successful theory for the origin of the planets should explain first-order planetary characteristics. The terrestrial planets include Mercury, Venus, Earth, and Mars. They are small ($10^{26\text{-}27}$g), "rocky" bodies characterized by oxidized atmospheres (except for Mercury, which has almost no atmosphere). Carbon dioxide is the most abundant constituent of the atmospheres of Venus and Mars and is hypothesized to have been one of the dominant constituents on the early Earth. Observed planetary densities imply some subtle differences between the terrestrial planets, e.g., Mars is less dense (3.94 g/cm^3) than Venus (5.25 g/cm^3), Mercury (5.44 g/cm^3), and Earth (5.52 g/cm^3). Although the uncompressed density of Mars (~3.7 g/cm^3) is similar to that of Venus and Earth (~4.0 g/cm^3), Mercury's uncompressed density (~5.3 g/cm^3) is much greater than that of the other terrestrial planets and cosmochemical considerations therefore require that it contain 60–70% iron, most of it probably concentrated in a large core (42% of the total volume). Proportionately, Mercury contains twice as much iron as any other terrestrial planet.

The giant gaseous planets, Jupiter and Saturn, are massive ($10^{29\text{-}30}$g) and rich in hydrogen and helium, although not as rich as the sun. (Jupiter has retained approximately one-third and Saturn approximately one-tenth of its original H and He). They are less dense (0.70 and 1.33 g/cm^3 for Saturn and Jupiter, respectively) than the terrestrial planets. Intermediate in mass ($10^{28\text{-}29}$g) and abundance of hydrogen and helium (only about 1% of the H and He retained) are Uranus and Neptune. The outermost planet, Pluto, and its satellite Charon, are presumably ice-rich bodies, more like the large satellites of the giant planets.

The planets have different rotational periods, ranging from 243 days for Venus to 0.41 days for Jupiter. Venus, Uranus, and Pluto spin in a retrograde sense. Many of the planets have obliquities within 30° of the perpendicular to the ecliptic plane, although Uranus is on its side (98°) and Venus is upside down (179°), suggesting rather violent accretional histories.

Most of the planets have orbits of moderate eccentricity (0.03–0.08). The small outliers, Mercury and Pluto, have highly eccentric orbits, 0.18 and 0.242, respectively. Most intriguing as dynamical clues are that Neptune's orbit is extraordinarily circular (0.009), Pluto is in a 2:3 resonance with Neptune, and the ratios of successive mean motion vary from 2.0 to 2.8 among the major planets.

Of the satellites of the terrestrial planets, the Earth's Moon is most significant. It is a large (10^{25}g), low-density (3.34 g/cm^3) object in comparison to Earth. In view of its extreme dryness, the Moon's low density requires that it be depleted in iron. The satellites of the outer planets exhibit dynamical regularities, some due to tidal evolution, some attributed to the circumstances of their origins. With the exception of the Galilean satellites, they do not seem to display systematic compositional variations as a function of distance from the primary.

We have made precise measurements of some compositional parameters of the terrestrial planets. For example, there are primordial variations in their isotopic compositions of oxygen (assuming that measurements made on SNC meteorites are appropriate for Mars, and that analyses of ordinary and carbonaceous chondrites reflect compositions in the asteroid belt). Similarly, there are differences in the abundances, abundance ratios, and isotopic ratios of the noble gases characteristic of Venus, Earth, Mars, and the asteroid belt. Some of the noble-gas differences, such as the Kr/Xe ratio, vary systematically as a function of distance from the sun. The noble gases do not significantly take part in the chemistry of these planetary bodies and thus may record evidence from which the original isotopic compositions or abundance ratios present during planetary accretion may be derived. Based on spectral measurements it has been established that S-type (i.e., stony or stony-iron) asteroids dominate in inner regions of the belt, whereas C-, D-, and P-type asteroids (all possibly carbonaceous) largely populate the outer regions. If the presently observed compositional structure of the asteroid belt is primordial then, taken together with the isotopic and noble-gas evidence cited above, it would appear that mixing was somewhat inefficient in the inner solar system.

Besides planets, their satellites, asteroids, and the sun, the solar system includes comets whose total mass, while uncertain, is thought to be between a few Earth masses and one Jupiter mass. The source region of comets, the Oort cloud, extends out to about 50,000 A.U. At least in its outermost regions, it is spherically disposed around the solar system, rather than restricted to the planetary plane. Comets are agglomerations of water ice and more refractory organic and silicate dust. They probably contain the most primitive (or least altered) materials in the solar system.

There is some evidence that melting was common in the early solar system. Several meteorites, thought to be derived from the asteroid belt, were at least partially molten 4.5 b.y. ago. This suggests that some asteroids melted at this time. In Earth, core formation is thought to have occurred contemporaneously with growth of the planet. Core formation involved metal/silicate segregation in a partially molten mantle. Some xenoliths from Earth's upper mantle have compositions suggesting that they are partial melts of the whole mantle; these partial melts possibly formed earlier than 4.0 b.y. ago.

Magnetic fields apparently existed 4.5 b.y. ago. Some meteorites show evidence for magnetic fields at the time when they formed and maybe even at an earlier stage when some of their constituent materials were still separate entities in the solar nebula.

The cratering record preserved on the ancient surfaces of some planetary bodies—the Moon, Mercury, the highland regions of Mars, and some outer solar system satellites—has been used to make an inventory of the size and abundance of material left over after planetary accretion was largely complete. The record of these populations differs at various heliocentric distances.

Accumulation of planetesimals currently is the most popular framework within which to develop a theory for the origin of the planets—a theory that is compatible with the aforementioned observed characteristics of our solar system. Some examples of major research areas with promise of scientific progress fall in six broad categories.

I. Agglomeration of Grains

The planetesimals that accumulated to form planets are themselves thought to have grown from even smaller grains. However, we know little about the characteristics of the grains and the processes by which they accumulated. For example, there is no detailed understanding of how grains become stuck together. Is a gravitational collapse mechanism involved? Do organics or ice act as a glue that promotes adhesion? Are surface forces between particles sufficient? One way to address this problem is through coagulation experiments in a microgravity environment such as that provided by the Space Station. Theoretical calculations may also be employed to evaluate the efficiency of these agglomeration processes, assuming reasonable estimates for the chemical and physical properties of the grains.

There is little understanding of the physics and chemistry of the incorporation of gas into (and loss of gas from) the grains. If gas incorporation occurs at low temperatures, it is likely to be a kinetic process rather than an equilibrium thermodynamic process. Nonetheless, little information is available on the kinetics or thermodynamics of the phenomenon. Experimental studies of the kinetics of gas-grain interactions may be necessary to model these processes.

We need to know the initial size and compositional spectrum of planetesimals formed by agglomerating grains. Icy planetesimals may be expected to behave in a different fashion than rocky planetesimals. What are the precise dynamical constraints involved?

II. Formation of the Giant and Intermediate Planets

Jupiter and Saturn are massive planets that apparently accumulated in the vicinity of a large volume of gas. It is unclear how rocky and icy planetesimals accumulated to form a core sufficiently large to allow gravitational collapse of nebula gases and the concentration of the required amounts of hydrogen and helium. Some workers think that the giant planets must have grown quickly, while there was a lot of gas available. The terrestrial planets present no evidence of forming under high nebula gas pressures. When and by what process was this gas removed?

It is important to understand the effect of the formation of the giant planets, particularly Jupiter, on the inner planets, the asteroid belt, and the outer planets. How does Jupiter's origin relate to the compositional structure of the asteroid belt? Why did rapid accretion occur for Jupiter and not in the asteroid belt?

For the outermost planets, particularly Neptune, calculations suggest that the amount of material present in their feeding zones is insufficient to allow accumulation on reasonable timescales. Old models for Neptune's accretion involve time scales of $\sim 10^{10}$ years. Resonance mechanisms, as suggested by the orbital properties mentioned earlier, may shorten these time scales, but quantitative models have not been developed. Hypotheses for the origin of the giant planets should be consistent with reasonable models for the intermediate planets.

III. Accumulation of the Terrestrial Planets

The limited quantitative numerical calculations of the accumulation of the terrestrial planets suggest that during growth their collisional history was quite violent, accompanied by high-velocity "giant impacts," sometimes within an order of magnitude of the gravitational binding energy of Earth-size planets. This was accompanied by widespread mixing of chemical compositions throughout the terrestrial planet region. It is quite possible, however, that the range of physical phenomena included in these calculations is incomplete, and that a more advanced treatment might lead to alternatives, possibly to a more "tranquil" series of events, and to the restoration of the more conventional idea of individual planetary "feeding zones" of special chemical compositions. An improved understanding of the initial chemical and physical states of the terrestrial planets is required to provide observational tests of such theories, and to stimulate the iteration of theory, observation, and experiment that is the hallmark of a healthy science.

IV. Gas-Dust, Planet-Disk Dynamical Interactions

It is uncertain how gas and dust dynamically interact and how planets and gas-dust disks interact. This information is required for an understanding of the formation of the Moon, the outer planet satellite systems, and the evolution of planetary rings. An understanding of gas gravitational instabilities would also be very useful. The requisite calculations could provide general knowledge applicable to the origin of giant gaseous protoplanets and binary star pairs.

V. Initial Chemical and Physical States of Sampled Objects

Current hypotheses for the origin of the Earth and the Moon require a hot, possibly molten initial state. Did the early Earth and Moon experience global melting, and if so, what were its consequences on core formation, mantle differentiation, crustal genesis, and atmospheric degassing? It is essential to determine if chemical or physical evidence for this melting event is preserved in early Archean mantle-derived magmatic rocks, upper mantle xenoliths, lunar basalts, anorthosites and breccias, and in any samples from other planets that become available (e.g., the SNC meteorites). In this regard, this research effort is an important complement to proposed sample-return missions, such as the Mars Rover Sample Return.

Geochemical studies of samples should also be used to define the precise chemical stratification of the Earth and the Moon at the completion of accretion. Such information would provide a way of distinguishing between homogeneous and heterogeneous accretion models. An essential component of these studies will be laboratory and numerical experiments simulating aspects of planetary accretion and differentiation, including atmospheric outgassing.

It is important to use the tectonic and geomorphic record preserved on the ancient surfaces of the planets to constrain the physical processes involved during accretion, global melting and degassing. The effects of large-scale impacts on the terrestrial planets as their atmospheres were forming should also be examined. Theoretical studies could be used to predict the amount of atmospheric erosion or addition resulting from large impacts. The number of impacts might be constrained from a knowledge of the timing of outgassing, the mass and composition of the atmosphere, and the composition of the impacting bodies.

VI. Planetary Accumulation and Planetary Atmospheres

The origins, early histories, and evolution of planetary atmospheres were closely related to the formation of the planets. There are fundamental deficiencies in our understanding of the relationships between the formation of the planets and their atmospheres. The planned planetary missions, Galileo and Cassini, will provide important compositional data for the atmospheres of Jupiter, Saturn, and Titan. Comparable data have already been collected for Venus, Earth, and Mars. Many questions concerning the earliest stages of atmospheric evolution remain unanswered. These include such fundamental issues as the following: What was the influence of large-scale bombardment on the formation of the atmospheres of the terrestrial planets and on their chemical composition? Was organic material delivered to the early Earth by impacting bodies? What was the survival rate of such organic material? How did large impacting bodies influence the origin and evolution of life on our planet? How was the chemical composition of the atmospheres of the terrestrial and outer planets influenced by planetary accumulation? What are the fates of the outgassed volatiles on the terrestrial planets?

RECOMMENDATIONS

The broad problems of the accumulation of planets from planetesimals, the addition of planetary volatiles (including the massive mantles of Jupiter and Saturn), and the subsequent early evolution of the planets can be addressed through three complementary approaches. These are: numerical and theoretical studies of planetary formation, experimental studies of physical and chemical processes relevant to planetary growth, and geochemical studies of meteorites and other appropriate planetary materials.

Within this broad framework many specific problems can be identified that may be pursued by independent investigators using one or more of these complementary approaches. For example, one such group of investigations of great importance are those directed toward understanding the physical and chemical mechanisms by which nebular dust particles aggregate to form small planetesimals. Another concerns the manner in which these planetesimals combine to form planetary bodies. In this regard, the formation of Jupiter's core and hydrogen-helium mantle is of special interest, inasmuch as phenomena initiated by an early-formed Jupiter could, to a large extent, control the subsequent evolution of the rest of the planetary system.

The asteroids are especially sensitive to events accompanying the formation of Jupiter. A better understanding of both the dynamical events to be expected in the asteroid belt and the related chemical, mineralogical, and isotopic effects observable in asteroidal meteorites is required in order to reveal the history of these events.

As results of the kind illustrated by these examples become available, these often specialized individual studies, oriented toward long-range goals, will combine to provide "building blocks" for the continuing grander effort of synthesizing the history of our solar system. In turn, we will gain a deeper understanding of the processes by which other planetary systems might form and evolve.

Section III:
Program Plan

PROGRAM PLAN FOR A DIRECTED STUDY EFFORT TO UNDERSTAND THE ORIGINS OF SOLAR SYSTEMS

SUBMITTED TO OSSA

BY

SOLAR SYSTEM EXPLORATION DIVISION
ASTROPHYSICS DIVISION
LIFE SCIENCES DIVISION

I. PROGRAM OVERVIEW

A. Science Goals

The 1958 Space Act that established NASA stated that one of the goals of the Agency is to "understand the origin of the Solar System," another is to "understand the origin of life. . .". Today we stand at the threshold of major advances toward these goals. Historically, the first of these goals has been pursued by studying the planets and primitive bodies within the solar system itself. However, the study of the birth of stars and of other planetary systems is essential to understanding the origin of our own solar system: Each of these processes has contributed to the origin and diversity of life as we know it. The program proposed here is aimed at expanding the historical approach to these problems with focused interdisciplinary research efforts that make use of solar system data as well as information about the environs and formation processes of other stellar and planetary systems. Thus, nebular models can provide a focus for astronomical observations of star-forming regions and for the analyses of isotopic heterogeneities in meteorites. Similarly, models and observations of the chemistry in interstellar clouds and the analysis of both interplanetary dust particles and individual meteoritic components can generate profound new insights into the structure and origin of comets, asteroids, and planets. Fusion of these approaches will lead to a multifaceted picture of the origins of solar systems and the prevalence of life in the universe that will be much more complete than that generated solely within the framework of any single scientific discipline.

B. Rationale and Timeliness

A formal program dedicated to the study of the origins of solar systems is ripe for establishment and requires an umbrella organization that encompasses at least three NASA divisions: Solar System Exploration, Astrophysics, and Life Sciences. Some of the most exciting future developments in these fields probably lie at the interfaces of early stellar evolution, planetary sciences, and exobiology. Important cross-fertilization should take place, for example, when solar nebula modelers confront the constraints set by the extensive meteoritic record and the recent, rapid growth in our knowledge of planetary interiors and atmospheres. An expanding program of planetary exploration will yield new data on the conditions required for the emergence of viable lifeforms, as well as data from which to infer the very earliest history of the solar system. The study of young stars and their nebular disks will provide more realistic constraints on the physical and chemical environments within the protosolar nebula. Such studies will test nebula models to an extent not possible by using data solely from our own solar system. Using this new data we may finally be able to delimit the time scale available for planetary formation.

Several imminent NASA missions make the current proposal especially timely; a focused research effort will ensure the maximum science return from limited R & A funds. The Space Station may allow the intact collection of interplanetary dust particles, permitting a detailed analysis of their structure, composition, and place of origin. Microgravity experiments in the Gas-Grain Simulation Facility could yield data on the physical characteristics of agglomerating dust grains. The Hubble Space Telescope (HST) will provide images of unparalleled clarity and angular resolution of the disks and jets associated with young stars. The presence of giant planets circling nearby stars may be revealed by HST or by the Astrometric Telescope Facility attached to the Space Station. The Space Infrared Telescope Facility (SIRTF) will make sensitive measurements of the infrared emission from regions of recent star formation, and it may also detect objects intermediate in their properties between stars and planets, the so-called brown dwarfs. Deep searches by the Advanced X-Ray Astrophysics Facility (AXAF) will greatly improve the statistics of the abundances of "classical" and "naked" T-Tauri stars, thereby setting useful limits on the lifetimes of the disks that exist around pre-main-sequence stars of low mass. The Gamma-Ray Observatory will provide a measure of the overall galactic abundances and distribution of radioactive elements, such as ^{26}Al, that are important factors in the chronology and early evolution of primitive solar system objects.

The Comet Rendezvous, Asteroid Flyby (CRAF) will rendevous with and send a probe into a comet and will also fly by an asteroid in a study of bodies that are thought to be similar to the basic building blocks of the giant and terrestrial planets. The Cometary Nucleus Sample Return Mission will bring back pristine material that dates from the birth of the solar system for analysis in terrestrial laboratories. The Galileo Project will examine at close range the atmosphere and the regular satellites of Jupiter, the dominant body orbiting the sun. Cassini will subject the atmospheres of Titan and Saturn to similar close scrutiny and will also improve our knowledge of the properties and behavior of particulate disks by closely examining Saturn's ring system. The Mars Rover Sample Return Mission will collect and return to Earth rock, soil, and even atmospheric samples of Mars for careful laboratory analysis. These samples will provide evidence for the gross chemical and isotopic composition of a planet 0.5 A.U. from Earth and may retain clues to the geological history of Mars, including the manner of its accumulation and details of its earliest evolution.

NASA is making significant investments to study and/or conduct the above missions. An indispensable component of this investment must be a directed and vigorous research and analysis program. To maximize the returns on one common purpose of all of these flight projects, we propose the funding of a focused, long-range research and analysis program on the "Origins of Solar Systems." A relatively small infusion of funds can buy tremendous progress from fruitful interactions between the traditionally separate scientific disciplines within NASA.

C. Timeline and Budget Summary

1 Mar 1989	Issue NASA Research Announcement (NRA)
31 Augt 1989	Proposal deadline
15 Sept 1989	Proposals assigned for division review
28–30 Nov 1989	Panel review of proposals
15 Dec 1989	Program selection
2 Jan 1990	Notification of selection
2 Jan 1990	Initiate funding

Total program budget of $6 million dollars per year

Approximate Budgetary Breakdown:

25 new investigators at $75K per P.I. per year	$1875K
50 investigators co-funded w/OSSA Divisions at $37.5K per P.I. per year	1875K
Equipment purchase and laboratory upgrade	1500K
3 consortia at $200K per consortium per year	600K
Workshop support	50K
Administrative costs (proposal review, support for steering committee activities)	100K

II. SCIENCE PLAN

A. Planning Background

Understanding the origin of our solar system appears as a major goal of NASA in long-range planning documents and in the scientific rationales for numerous research and flight programs and has done so since the agency was founded. However, efforts directed primarily toward understanding the formation of the sun and planets *per se* have constituted only a minor fraction of the NASA budget. Scientific communities that study different aspects of the origin of our solar system, and of other solar systems, have never been supported by a broad NASA program dedicated specifically to interdisciplinary scientific research.

In recognition of this need, a workshop was convened in December 1986 to identify types of high-priority scientific investigations that would profitably address the problem of the origins of solar systems. About 40 scientists from a number of disciplines, ranging from astronomers and interstellar chemists to meteoriticists and planetary geologists, attended the workshop. In a plenary session, tutorials by recognized experts reviewed the present state of scientific knowledge relevant to the origins of solar systems. Based on discussions that followed the tutorials, four working groups were established. Each working group formulated the general outlines of a scientific plan for interdisciplinary studies affecting their respective areas. The plans were discussed and revised in a subsequent plenary session.

In December 1987, another workshop was held to review written versions of the plans. This smaller group of scientists also formulated and recommended the Program Plan that is included in this report.

B. Opportunities for Interdisciplinary Research

Focused, interdisciplinary research efforts can be expected to produce dramatic advances in our understanding of the origins of planetary systems in four general areas. These opportunities have been documented over the course of two workshops by active researchers from the fields of astrophysics, meteoritics, exobiology, and planetary sciences. None of the participants at the meetings suggested that these four areas are the only fields in which breakthrough research is possible. However, these areas offer many examples of the type of interdisciplinary research that could yield significant advances in our understanding of the processes by which planetary systems form.

One working group recommended specific studies to explore the relationships between interstellar chemistry and individual components of primitive bodies such as comets and meteorites. A second explored the possibility for synergism between nebula models and astronomical observations of protostellar sources, while a third group explored the possibility that meteoritic data may now be used to place more rigorous constraints on nebula models. The fourth working group proposed detailed, analytical studies of the compositions and structures of the atmospheres, surfaces, and interiors of the planets that, when combined with appropriate theoretical and experimental studies, could infer the mechanisms and time scales for the accumulation and evolution of individual planets. Detailed recommendations from each of the four working groups are available in the *Workshop on the Origins of Solar Systems*, published by the Lunar and Planetary Institute as LPI Technical Report 88-04, and as a volume in the NASA Conference Proceedings series.

III. PROGRAM MANAGEMENT

A. Management Philosophy

Implementation of an interdisciplinary program with the broad goal of understanding the origins of solar systems presents the opportunity for unique scientific cooperation among several divisions of OSSA. Program management should foster this cooperation. At least three NASA divisions—Solar System Exploration, Life Sciences, and Astrophysics—and their constituent scientific communities will be involved. However, other divisions, such as Earth Sciences and Solar Physics, may find that their broad research goals are also compatible with the Origins of Solar Systems Program. Thus, the management structure adopted for this program should be flexible enough to include as many divisional partners as necessary.

Management of the Origins of Solar Systems Program should aim to maximize the scientific return of funded investigations. Research that crosses traditional boundaries between scientific fields should be encouraged in the NRA. The review process should ensure that a well-integrated program of high-quality research, encompassing an appropriate number of collaborative, interdisciplinary investigations, is established. Workshops, symposia, and conferences that bring together workers with diverse scientific backgrounds should be funded as part of the research program.

B. Recommended Management Structure

The nature of this research effort requires the establishment of a management structure for the oversight of this program at the level of the Assistant Associate Administrator for Science in the Office of Space Science and Applications. The Assistant Associate Administrator should establish an interdisciplinary steering committee for this program in consultation with the Directors of the Astrophysics, Life Sciences, and Solar System Exploration Divisions. This steering committee will serve two main functions: (1) to provide overall direction for the program, and (2) to ensure program balance between scientific disciplines, particularly at the final stage of the review process when individual division reviews are merged. Another function of the steering committee will be to ensure the continued cross-disciplinary fertilization of research efforts by organizing appropriate workshops, conferences, and symposia that bridge traditional discipline boundaries.

As proposals are received by the program office in response to the NASA Research Announcement (NRA), the steering committee will assign the proposals to the appropriate division for peer review using the procedures appropriate to that particular division. After peer review the steering committee will recommend a research program of the highest possible quality. The research program should meet the scientific objectives of the initiative and provide an equitable balance between laboratory, observational, and theoretical efforts.

We recommend that the steering committee be constituted to include representatives of the Division Directors and approximately a dozen scientists appointed by the Assistant Associate Administrator. The chair of the committee would be selected from among the scientists for a term of three years. To provide continuity in the long-range planning, it would probably be desirable to institute staggered terms of office after the initial constitution of the committee.

The program should be managed through the established divisional discipline offices with oversight by the Assistant Associate Administrator of OSSA for Science. The divisional discipline scientists will be the routine contact points for principal investigators supported by the program. Grants/contracts to these investigators will be monitored by these discipline scientists in the same manner as other components of their ongoing research programs. Thus, management responsibility for the program would be spread across divisional boundaries, without infringing on the management autonomy of any division. Such a management structure will efficiently utilize the scientific expertise within each division while not burdening any division disproportionately. Although oversight responsibility for the program would be in the Office of the Assistant Associate Administrator for Science, it is not expected to constitute a significant administrative burden on this office as much of the day-to-day responsibility for the program will rest with the divisional discipline scientists. A significant proportion of the long-range planning, review, and integration of the program will be performed by the steering committee.

C. Mechanisms

An approach to the problem of solar system origin that takes advantage of the available data, and gives effective guidance to further data collection, necessarily entails a wide range of expertise. Hence, as discussed in Section IIB, there are several research areas where interdisciplinary interaction is needed. This interaction will vary greatly, from general suggestions that investigations within one discipline might help to answer questions generated by another, to detailed day-by-day collaboration wherein models from different disciplines are integrated. An example of the former would be data from a comet-flyby mission that might redirect laboratory experiments on hydrocarbons. An example of the latter type of interaction would be a study of nonequilibrium processes affecting meteorite structure and chemistry that integrates both fluid dynamical and chemical expertise.

To foster interaction, and to achieve a well-balanced and integrated program, a variety of mechanisms should be explored. The first element in an effective interdisciplinary program is farsighted, realistic overall planning that continues throughout the program. The initial phases of this task have been attempted during the second workshop. An effective continuation requires a steering group that includes both NASA managers and interested scientists, as detailed in Section IIIB above. Careful attention should be paid to drafting and distribution of the NRA so that all appropriate scientific communities are informed of this opportunity. The NRA should encourage investigators to propose worthy research that in the past has fallen through the cracks between existing disciplinary programs. The review process should ensure not only technical competence, as can be gauged through the normal discipline review process, but also that each study constitutes an effective contribution to the goals of the program. A two-tiered review process, involving direct input from the steering committee, may be required.

The NRA should explicitly encourage the formation of focused, multidiscipline research consortia and means should be explored to make multi-institutional consortia convenient (e.g., avoiding double overhead). The steering group should decide which problem areas might be appropriate as consortia and what forms such consortia might take. Proposed consortia must demonstrate access to the range of research facilities required to achieve their scientific goals. The steering group should ensure that individual scientists or research institutions involved in each project have the necessary resources (e.g., ion probes or parallel processing supercomputers) at their disposal.

Investigators selected to participate in the Origins of Solar Systems Program should meet initially to discuss the general scientific goals and constraints of the program. Meetings at two- or three-year intervals at which all supported investigators are expected to present the results of their research efforts might also be considered. More focused workshops devoted to particular problem areas should also be encouraged and supported. These would occur at more frequent intervals (two to three per year). The particular topics to be addressed in the workshops might be suggested and organized by members of the steering committee or by interested members of the scientific community.

IV. PROPOSED BUDGET AND IMPLEMENTATION

A. Proposed Budget

The program involves the participation of the Life Sciences, Solar System Exploration, and Astrophysics Divisions. Funding for this program is intended both to augment existing R & A within these divisions and to provide for new research efforts previously unsupported within any division. Six budget elements are envisioned:

1. *Twenty-five individual principal investigators (P.I.s) at an average grant of $75K per P.I.* These investigators are typically new to NASA research programs and would be supported entirely by the Origins of Solar Systems Program.

2. *Fifty individual P.I.s at an average cost to the Origins of Solar Systems Program of $37.5K per P.I.* These investigators constitute a group who are already supported to a large extent by one of the existing OSSA Divisions and who wish to expand their ongoing research efforts in response to the NRA. In these instances the Origins of Solar Systems Program would provide matching funds to the individual discipline scientist to support such an expansion.

3. *A small number of multi-investigator, cross-disciplinary research consortia at an average cost of $200K per consortium.* Members of consortia may receive support from the OSSA divisions, from the Origins of Solar Systems Program, or from other sources and still receive support for their part in a particular consortium provided that their individual task is not already part of their ongoing research effort.

4. *Purchase and upgrade of research equipment.* Although it is not expected that the Origins of Solar Systems Program will be able to provide funding for major new equipment purchases, funds from this program could be used to make significant upgrades in the capabilities of existing laboratories, computer systems, or observational facilities where such upgrades will enable the facility to be used for research that is responsive to the goals of the program.

5. *Workshop, conference, and symposia support as appropriate to the size of the meeting.* Funding might range from as little as a few thousand dollars for a small workshop up to as much as twenty-five thousand dollars to help support a large conference.

6. *Administrative costs.* These would include the services of an organization such as the Lunar and Planetary Institute to coordinate the efforts and to pay the expenses of the steering group, to assist in the arrangement of meetings (including any panel review process), to publish the proceedings of workshops, and to inform the community of progress in relevant research efforts.

Annual Budget:

1.	25 new investigators	$1875K
2.	50 co-funded investigators	1875K
3.	3 research consortia	600K
4.	Equipment purchase and upgrade	1500K
5.	Workshop, conference, and symposia support	50K
6.	Administrative costs	100K
TOTAL		$6000K

B. Program Implementation

In order to enable systematic, long-range planning on the part of both principal investigators and program managers, we suggest that individual grants be made for periods of up to and including three years whenever feasible. Brief annual progress reports coupled with copies of papers published or submitted for publication should be adequate to allow responsible oversight of the individual grants. It is expected that appreciably less than the maximum possible number of three-year proposals would be funded in the first year, however, so that in subsequent years, newly-submitted, outstanding proposals could be funded with new money.

We propose that this program be initiated with the understanding that at least two cycles of three-year proposals will be funded, followed by an overall evaluation of the program. A single cycle of three-year proposals is an inadequate period for properly evaluating the impact of this new program. However, we would hope that the first six years of research would be so fruitful as to be the strongest argument in favor of continuing support.

V. CONCLUSIONS

In a large research and analysis program the establishment of a discipline-oriented management structure, such as that which exists within OSSA, inevitably serves to discourage the coordinated pursuit of research efforts that fall across the purview of several disciplines. Although each of the three OSSA divisions represented at our workshops supports research related to the origins of solar systems, there is no mechanism by which these efforts are coordinated in order to encourage maximum scientific progress. By necessity, each OSSA division manages its research and analysis programs in order to lend maximum support to its own space flight efforts. Although each of these flight programs addresses one or more important, basic, scientific questions, there are broader goals such as "... understanding the origin of the solar system" (NASA Charter) that can only be addressed by the synergistic combination of experimental, theoretical, and spacecraft data from several disciplines. In recognition of this fact, participants at two workshops on the origins of solar systems have recommended that a focused research and analysis program be established at the level of the Assistant Associate Administrator for Science in the Office of Space Science and Applications. A relatively modest investment ($6M per year) should yield benefits to each of the three divisions' flight and R & A programs. In addition, this program should greatly increase our knowledge of the processes by which our own solar system formed, provide a much better understanding of the probability of the occurrence of such processes throughout the universe, and lead to theoretical predictions that can be tested by new observations of current star-forming regions.

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