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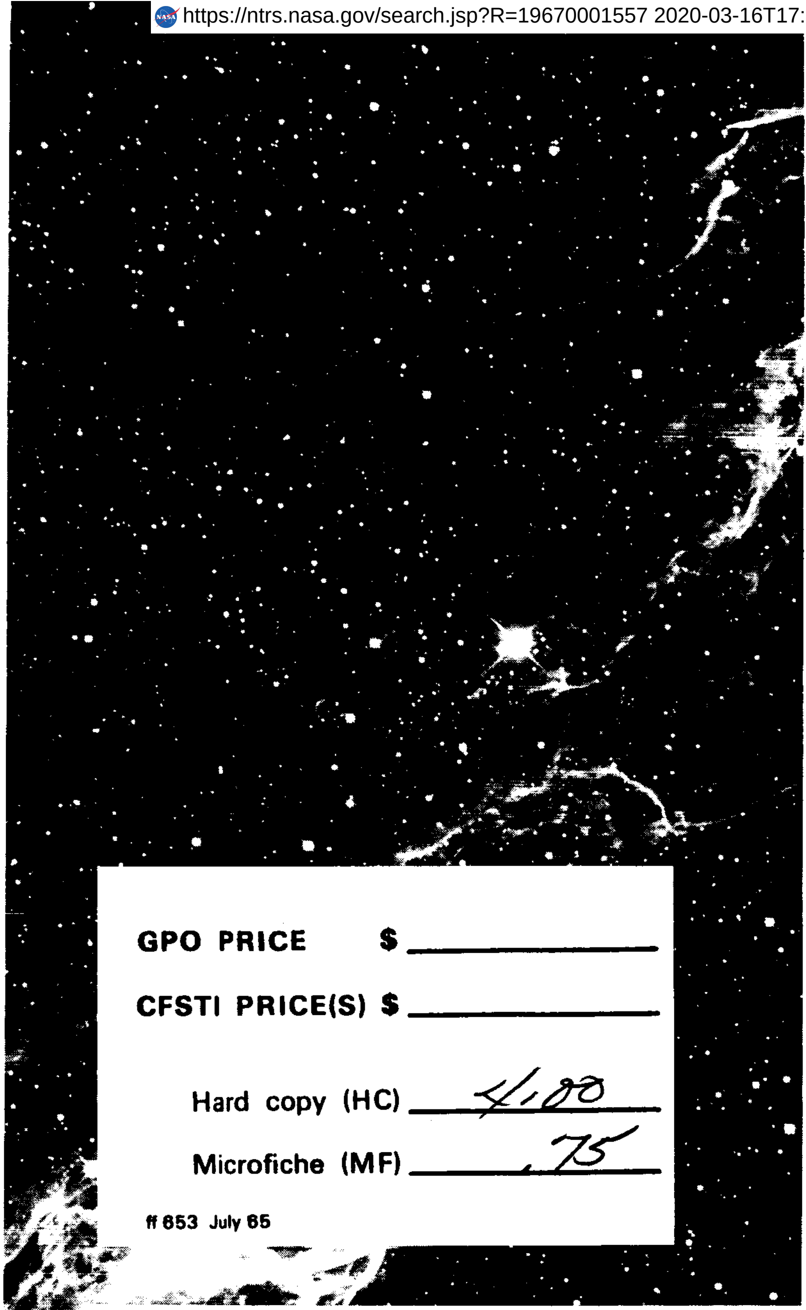

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Report P-18

SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS: THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

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SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS: THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

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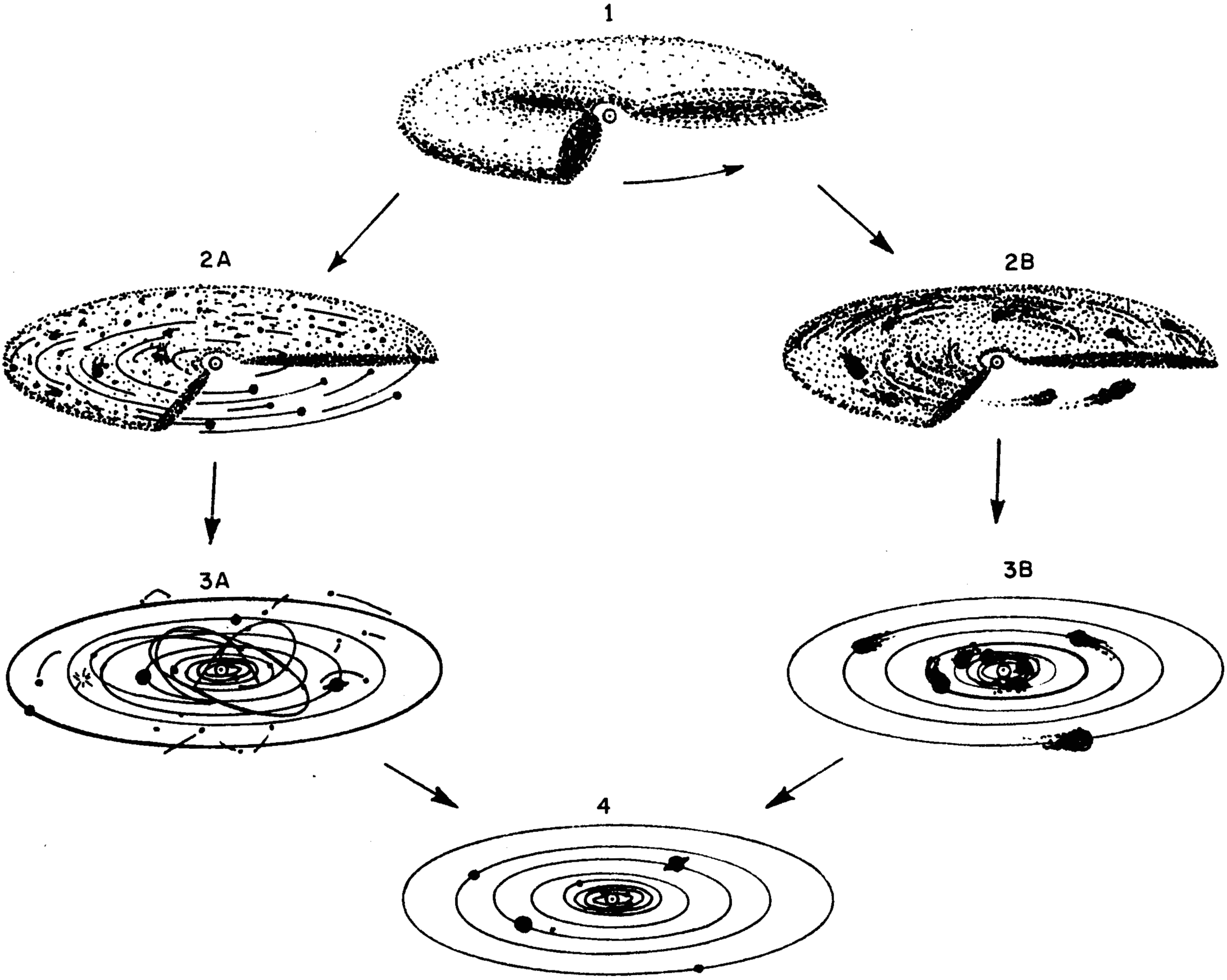
FORMATION OF PLANETS FROM A SOLAR NEBULA



LEFT: PLANETS FORM FROM PLANETESIMALS
RIGHT: PLANETS FORM FROM PROTOPLANETS

The starting point is a solar nebula shown in 1, with counterclockwise rotation. In planetesimal theories (Schmidt, Von Weizsäcker, Fowler, Greenstein and Hoyle, Urey, and Cameron) bodies much smaller than a planet are formed (2A), residue gases are swept up or escape, interplanetesimal perturbations give less-ordered orbits (3A), and planets form by accretion (4). In protoplanet theories (Kuiper) a few condensations occur (2B), and collect much of the interplanetary gas (3B). Finally, light gases are lost by evaporation and the protoplanets of (3B) shrink to planets (4).

SUMMARY

Understanding the origin and evolution of the solar system is one of the primary goals of the space program and many spacecraft experiments and missions contribute to this goal. However the relationship between the individual experiments proposed and this goal is often tenuous. The purpose of this study has been to isolate spacecraft measurements and other future work which are <u>closely</u> tied to an understanding of the origin and evolution of the solar system.

Three broad areas of study have been pursued:

(1) Present day observations, theories, and experiments which are thought to be boundary conditions on the origin and evolution of the solar system, i.e., facts which must be explained by any complete theory.

(2) A broad sampling and critique of the more prominent theories which have been derived to explain the origin and evolution of the solar system, and

(3) Future work and experimentation which is necessary to advance our understanding, either by distinguishing among proposed theories, or by contributing to or further defining existing boundary conditions.

A discussion of the reliability one can place on each of the suggested boundary conditions is given. Where possible, the boundary conditions have been examined as to whether they should be placed on theories of origin or on theories of evolution of the solar system.

The boundary conditions thought to be most relevant to theories of the origin and evolution of the solar system are:

(1) The angular momentum per unit mass of the Sun is less than that of the planets by a factor of more than 10,000.

(2) The Sun's rotation speed is not unusual when compared to other stars of the same spectral class.

(3) The Sun was probably very large and bright for $\sim 10^6$ years; it was then very active during some or all of the next $\sim 10^7$ years; its surface temperature probably never exceeded $\sim$6000°K.

(4) The inclinations and eccentricities of the planets and asteroids are very low; their orbital radii follow an empirical law (Bode's law) approximately.

(5) Regular satellites have extremely low inclinations and eccentricities; their orbital radii follow a "Bode's law" less well than do the planets.

(6) The planets and asteroids rotate with small variations in period, except for Venus, Mercury and Pluto; they tend to have fairly low obliquity.

(7) The average spatial distribution of matter in the solar system.

(8) Based on gross physical properties, planets fall into two classes, Jovian (large, low density, low molecular weight) and terrestrial (small, high density, high molecular weight).

(9) The uncompressed densities of terrestrial planets decrease (slightly) with increasing solar distance.

(10) The Earth, and probably other terrestrial planets, have much smaller than cosmic abundance of highly volatile elements, including those of high molecular weight.

(11) Relative abundances of elements which differ in volatility by orders of magnitudes at elevated temperatures, but not at ~300°K, do not depart significantly from cosmic abundance.

(12) The ratio of deuterium to hydrogen is 1.5×10^{-4}, the ratio of Li^6 to Li^7 is .080; the ratio of B^{10} to B^{11} is .232.

(13) Isotopes of xenon and silver which are β-decay products of radioactive nuclides are overabundant in meteorites.

A large number of theories have been proposed to explain the origin and evolution of the solar system, based on some of the boundary conditions. Almost all theories fall into three classes:

(1) "Catastrophic" theories postulate a Sun-star encounter,

(2) "Evolutionary" theories form the entire solar system out of a single contracting cloud of interstellar material, and

(3) "Mixed" theories postulate a Sun-interstellar cloud encounter.

Many more theories have been proposed than are considered here. Catastrophic theories were once popular. However, they fail to account for certain very important boundary conditions and are not treated in detail.

Evolutionary theories are confronted with a serious problem in accounting for the angular momentum distribution in the solar system. New fluid dynamical and hydromagnetic principles can make such theories at least plausible. A number of such evolutionary theories have been summarized. The "mixed" theory of Schmidt and his collaborators has also been considered.

The theories tend to diverge at a number of points, some of which are quite fundamental:

(1) Did the entire solar system originate from a single cloud, or did a pre-existing Sun capture part of an interstellar cloud which ultimately formed planets?

(2) If the single cloud theory is correct, how did the Sun lose or fail to acquire considerable angular momentum?

(3) Did planets grow from planetesimals or shrink from protoplanets?

Strengths and weaknesses of each theory considered are pointed out, and a comparison between results of each theory and the boundary conditions set forth earlier has been used to determine those spacecraft measurements and other work which are most closely related to solar system origin and evolution.

Future work having the highest importance is:

(1) Measurements of interstellar composition, including isotopic ratios, on a mission to solar system escape. This would provide a significant new boundary condition on theories of solar system origin by obtaining a "cosmic abundance" more realistic than presently available, and may modify existing boundary conditions.

(2) Measurements of the isotopic ratio(s) $Li^6:Li^7$, $B^{10}:B^{11}$ and/or $C^{13}:C^{12}$ on a Jovian planet or a comet. The results would contribute to settling the problem of planetary formation from protoplanets vs. planetesimals.

Other knowledge of clear importance to understanding the origin and evolution of the solar system is:

(3) He:H ratio on the Jovian planets, especially Jupiter.

(4) The evolution of stars in their pre-main-sequence phase.

(5) Xenon (and silver, if possible) isotopic ratios on planets, satellites, asteroids, comets.

(6) The density of Mercury.

(7) The magnetic field properties of the planets.

(8) The heat flux from lunar and planetary interiors.

(9) The equation of state of iron-nickel, silicates, hydrogen under high pressure.

(10) Could the planets have been highly inclined or eccentric after their formation?

(11) The spatial density of, and conditions inside, interstellar clouds.

(12) The frequency of planetary systems.

(13) Interstellar density, temperature, magnetic field.

(14) Cloud contraction theory.

(15) The conditions, if any, under which planetesimals can accrete to form planets.

(16) The exospheric temperatures of each planet.

(17) The high velocity distribution of velocities in the exosphere, at least of Earth.

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SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS: THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

1. INTRODUCTION AND DEFINITIONS

1.1 Introduction

One of the goals of the space program is to provide an understanding of the origin and evolution of the solar system. The purpose of this report is to point out specific future work directly aimed at answering the present questions regarding the origin and evolution of the solar system. Sometimes particular experiments and missions are partially justified with the assertion that the results would increase knowledge of the solar system origin and/or evolution. Although such experiments and missions may lead to a desirable increase of knowledge of natural science, many have only an indirect bearing on the origin and evolution of the solar system.

Man's progress in understanding the origin and evolution has come on two fronts. As more and more was learned about natural science, some facts appeared which seemed relevant to the origin and evolution of the system, such as the low inclinations and eccentricities of the known planets. Theorists then attempted to explain these observable features with a theory of solar system origin and evolution consistent with known physical laws. Throughout history more facts became available, and new and more complete theories were generated.

The facts relevant to solar system origin and evolution are called "boundary conditions" in this report. It is necessary (but not sufficient) that a theory of solar system origin and evolution fit all boundary conditions, if it is to be correct.

The first main section of this report is concerned with boundary conditions; the second with theories; the last with future work which would increase knowledge of boundary conditions, or settle theoretical controversies, or both.

Boundary conditions which are presently known are set down in as objective a manner as possible and are discussed. An attempt is made to judge whether certain features now observed in the solar system are stable over its five billion year lifetime, and thus require an explanation by a theory for the <u>origin</u> of the solar system. These can be distinguished from those which could have come about in a slow fashion during the lifetime of the solar system, and may be explained by a theory for the <u>evolution</u> of the solar system.

It would be impossible to consider in any detail all or most of the theories of the origin and evolution of the solar system - far too many have been proposed. Newly discovered boundary conditions or detailed calculations have made many theories, such as those involving a star-Sun encounter, untenable. These are dismissed after a brief discussion.

A representative sample of influential, perhaps correct, theories are considered in more detail.

Each theory is summarized briefly, and its strengths and weaknesses are pointed out. Finally, a comparison of theory-boundary conditions is drawn, in order to determine whether the theory accounts for a boundary condition, does not account for it, or is contradicted by the boundary condition.

These discussions of boundary conditions, theories, and their interactions serve as a basis for future work. We envision the aim of such work to establish, extend, modify, or reject boundary conditions, and to outline methods by which existing controversies among theories can be settled.

1.2 Definitions

Some terms which are specific to solar system origin and evolution are used frequently in this report. For convenience, they are defined here:

Origin of the solar system: Spans relevant events prior to and including planet formation.

Evolution of the solar system: Spans relevant events after planet formation.

Boundary condition: Observable facts which must be fit by theories of solar system origin and evolution.

Solar nebula: A cloud of material in solar orbit, usually in the shape of a flattened ellipsoid, out of which planets form, according to most theories.

Evolutionary theory: A theory in which the entire solar system forms out of a single cloud of matter.

Mixed theory: A theory in which a pre-existing Sun captures a cloud of material to generate a solar nebula.

Catastrophic theory: A theory in which a pre-existing Sun is disrupted by one or more large celestial objects, such as another star.

Planetesimal: An object smaller than a planet which becomes part of a planet.

Protoplanet: An object larger than a planet which shrinks to become a planet.

2. BOUNDARY CONDITIONS ON THEORIES OF THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

The basis for understanding the origin and evolution of the solar system lies in those presently observed features that impose boundary conditions on theories. Some boundary conditions have been known and appreciated longer than others; these are discussed in detail and criticized. The more recently known boundary conditions, which will probably become more important for future theories, are also considered.

2.1 Angular Momentum Distribution

The angular momentum of a system of particles about some point is defined by the relation

$$N = \sum_i m_i (v_i \times r_i) ,$$

where m_i is the mass of a particular particle, v_i is its velocity, and r_i is the radius vector from an arbitrary origin. If the origin is chosen at the center of mass of the solar system, then the Sun contributes less than 2 percent to the solar system's angular momentum (mostly by rotation), and the planets contribute more than 98 percent (mostly by orbital motion). Since the Sun contains more than 99 percent of the mass of the solar system, a boundary condition on the origin and evolution of the solar system arises:

> THE ANGULAR MOMENTUM PER UNIT MASS OF THE SUN IS <u>LESS</u> THAN THAT OF THE PLANETS BY A FACTOR OF MORE THAN 10,000.

The angular momentum of a system is a constant of the motion unless torques are applied. Since torques are difficult to apply (they are absent in central force fields), the uneven angular momentum distribution is not easily explained. In fact, the older evolutionary theories were unable to overcome this boundary condition and were in disfavor until the last few decades. Explaining the angular momentum distribution by fluid coupling of angular momentum from the Sun to the planets constitutes a major portion of recently proposed theories, which are mostly evolutionary.

2.2 Astronomical Boundary Conditions

Astronomical evidence has provided some tentative answers to the questions: (1) Does the Sun possess unusual rotation properties, relative to other stars? (A "yes" would imply a special solution to the angular momentum problem; a "no" would extend the problem to other stars and require a general solution.) (2) How does a star which will become "sun-like" appear during its early stages of formation?

2.2.1 Other Solar System and Stellar Rotation Properties

The Sun has rotation properties no different from those that can be observed for stars of the same mass and luminosity. This, coupled with a "direct" observation, suggests that planetary systems are not an extremely uncommon feature of stars, as was once widely thought.

The obvious test of the commonness of planetary systems would be to see them near other stars, or else to show that they are absent and should be seen if present. Gravitational perturbations on a central star are presently the most sensitive indicator of the presence of a planet. Planets of the size of Jupiter near the closest few stars are detectable. In this way, a companion to Barnard's star only slightly larger than Jupiter (1.5 M_J) has recently been detected (van de Kamp 1963).

A more indirect test of the commonness of planetary system is to note whether our Sun possesses unusual rotation properties as a result of an unusual event.

Two kinds of evidence exist. One is the evidence from multiple star systems. It is generally assumed on the basis of observations of those stars which are close enough or bright enough to be examined that over fifty percent of the stars in our galaxy are members of binary or multiple star systems. Furthermore, the mean value of the separations of the components in all binaries that have been investigated is about 20 AU, about the same order as the distance of major planets from the Sun (Jupiter 5 AU, Neptune 30 AU). Thus one has the impression that the formation of multiple systems is a common occurrence. The solar system could then be some sort of degenerate double star in which the mass of the companion was divided up among the planets, comets, and asteroids (and some lost), instead of forming another star (Huang 1957,1959; Kuiper 1951).

The other piece of astronomical evidence showing the Sun's similarity to other stars is the rotation rates of other stars like the Sun. Many astronomers once felt that the angular momentum problem could best be solved by an unusual event leading to the transfer of angular momentum from the Sun into the forming planets. With this hypothesis one would expect that most stars like the Sun should contain about the same angular momentum as our entire solar system, since it was assumed that planet formation was very uncommon.

The observations contradict this conclusion. Figure 1 shows the observed dependence of rotation rate of single stars on spectral type (Burbidge and Burbidge 1958). Using results of stellar interior theory (Arp 1958, Harris et al. 1963), we show the relation between the observed spectral type and the stellar masses and radii in the lower part of Figure 1.

The dotted line shows the lower limit for the detectability of stellar rotations. No star less massive than those of spectral class F5 has been detected as having rotation except the Sun whose low rotation rate can be observed directly. This implies that such stars have rotation speeds below 25 km/sec. If G2 stars (the Sun's spectral class) had the angular momentum of our entire solar system, their rotation speeds would be of the order of 100 km/sec, and would have been measured. Since no stars like this have been found, the hypothesis that most stars like the

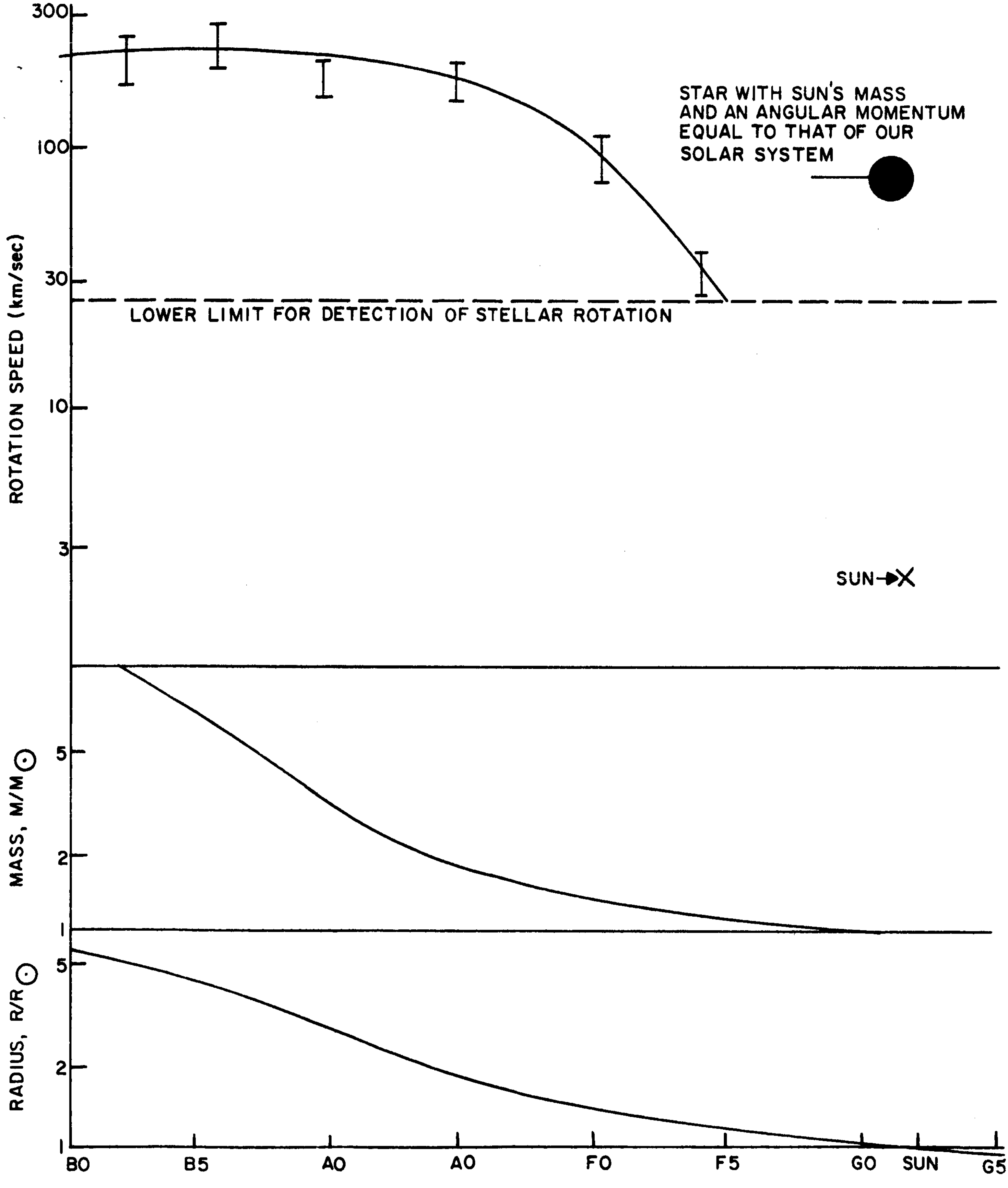

FIGURE 1. STELLAR ROTATIONS. THE TOP CURVE IS AN EMPIRICAL FIT TO THE OBSERVED ROTATION SPEEDS WHICH ARE SHOWN AS ERROR BARS. EXCEPT FOR THE SUN, ONLY ROTATION SPEEDS ABOVE 25 km/sec ARE DETECTABLE. THEORETICALLY CALCULATED MASSES AND RADII ARE SHOWN FOR THE OBSERVED SPECTRAL TYPES.

Sun should contain about the same angular momentum as our entire solar system is incorrect.

Many modern astronomers have gone further, maintaining that the rapid drop in rotation rates of stars with decrease in star mass implies the existence of planetary systems for the lighter stars. Their viewpoint has been summed up by Struve (1962):

> Thus there appears to be good evidence for assuming that the angular momentum of a star, caused by its own axial rotation, is preserved over long intervals of time. It also can be assumed that, presumably, the discontinuity on the main sequence at F5 is not caused by the braking action of magnetic fields or by other phenomena that would operate "smoothly" along the entire spread of the H-R [Hertzsprung-Russell] diagram, but that the discontinuity represents a rather fundamental difference in the manner in which the stars have been formed. Presumably main-sequence stars of spectral type F5 and later* have formed planetary systems that have absorbed most of the angular momentum of the original protostar; stars of earlier spectral type* are either devoid of planetary systems or have at least preserved within the star itself the major part of its original angular momentum.

The overall conclusions of the astronomical studies are, then, (1) formation of planets by an unusual event is not demanded by the Sun's low angular momentum (relative to the planets), because it is not necessarily low compared to other stars of similar spectral class, and (2) it is likely that the low rotation rates of single stars less massive than those of

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*For historical reasons, massive luminous stars on the main sequence are called "early stars" and light, dim stars on the main sequence are called "late stars". Evolution of stars in a direction along the main sequence is no longer thought to occur.

spectral class F5 are the result of planetary formation. The boundary condition on theories of the origin and evolution of the solar system is:

> THE SUN'S ROTATION SPEED IS <u>NOT UNUSUAL</u> WHEN COMPARED TO OTHER STARS OF THE SAME SPECTRAL CLASS.

2.2.2 Evolution of Very Young Stars

Most or all stars like our Sun are born out of a contracting cloud composed mostly of hydrogen. The star becomes luminous by conversion of gravitational potential energy to heat long before it reaches solar dimensions and before nuclear reactions begin. After further contraction, nuclear reactions provide the energy source, and the star evolves to the main sequence, where its external characteristics remain nearly constant for several billion years.

Recent, widely-accepted, pre-main-sequence calculations have been made by Hayashi (1961, 1966). Figure 2, which is taken from Hayashi (1966), shows the evolutionary track of a star of solar mass and composition as it heads toward the main sequence. By the time its radius is of the order of magnitude of Mercury's present orbit, the star has reached a surface temperature of about 4000°K and its luminosity is much greater than the present-day Sun's. As can be seen on the downward leg of Figure 2, it contracts almost isothermally in a very short time ($\sim$2 million years). It then heats up to a surface temperature of about 6000°K at essentially constant luminosity

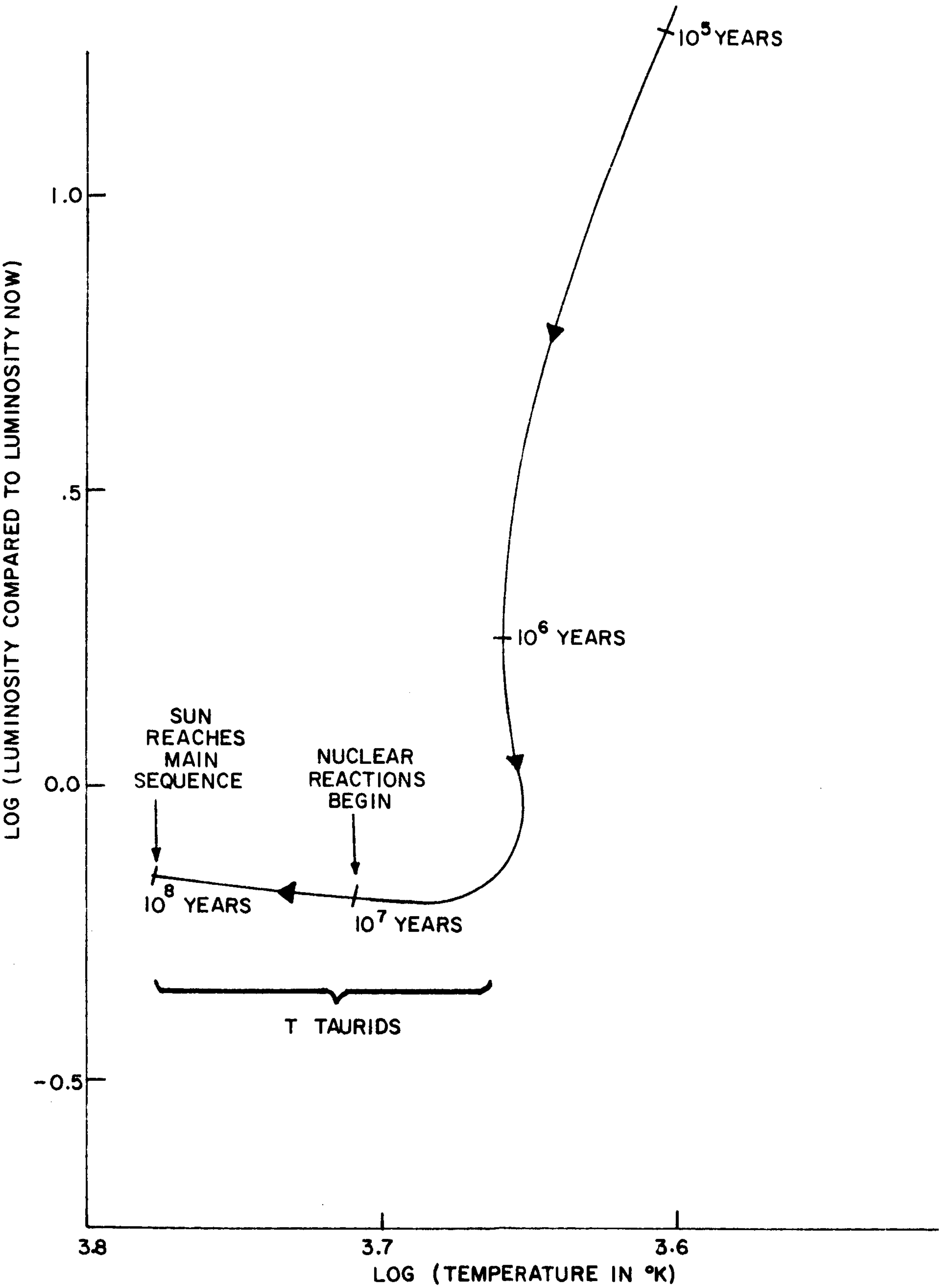


FIGURE 2. SOLAR EVOLUTION TO THE MAIN SEQUENCE

(the leftward leg of Fig. 2) in about 10 million years.

Hayashi's evolutionary track should be regarded as rather speculative at this time. His calculations depend on an assumption of convective mixing; if the magnetic fields inhibit this convection, then the constant temperature contraction is replaced by a constant luminosity contraction and the evolution to the main sequence is slower by an order of magnitude (Faulkner et al. 1963).

A number of stars have been observed which are thought to have approximatly the same mass as the Sun, and which have not yet reached the main sequence. These are called T-Tauri stars, and have been investigated most extensively by G. H. Herbig. They are characterized by enormous stellar winds, such that the mass loss can exceed 10^{-7} $M_{\odot}$ per year (Kuhi 1966). Presumably, large magnetic fields and chromospheric flares are associated with such activity.

Thus astronomical evidence indicates another boundary condition to theories of the origin and evolution of the solar system:

> THE SUN WAS PROBABLY VERY LARGE AND BRIGHT FOR $\sim 10^6$ YEARS; IT WAS THEN VERY ACTIVE DURING SOME OR ALL OF THE NEXT $\sim 10^7$ YEARS; ITS SURFACE TEMPERATURE PROBABLY NEVER EXCEEDED $\sim$6000°K.

2.3 Dynamical Boundary Conditions

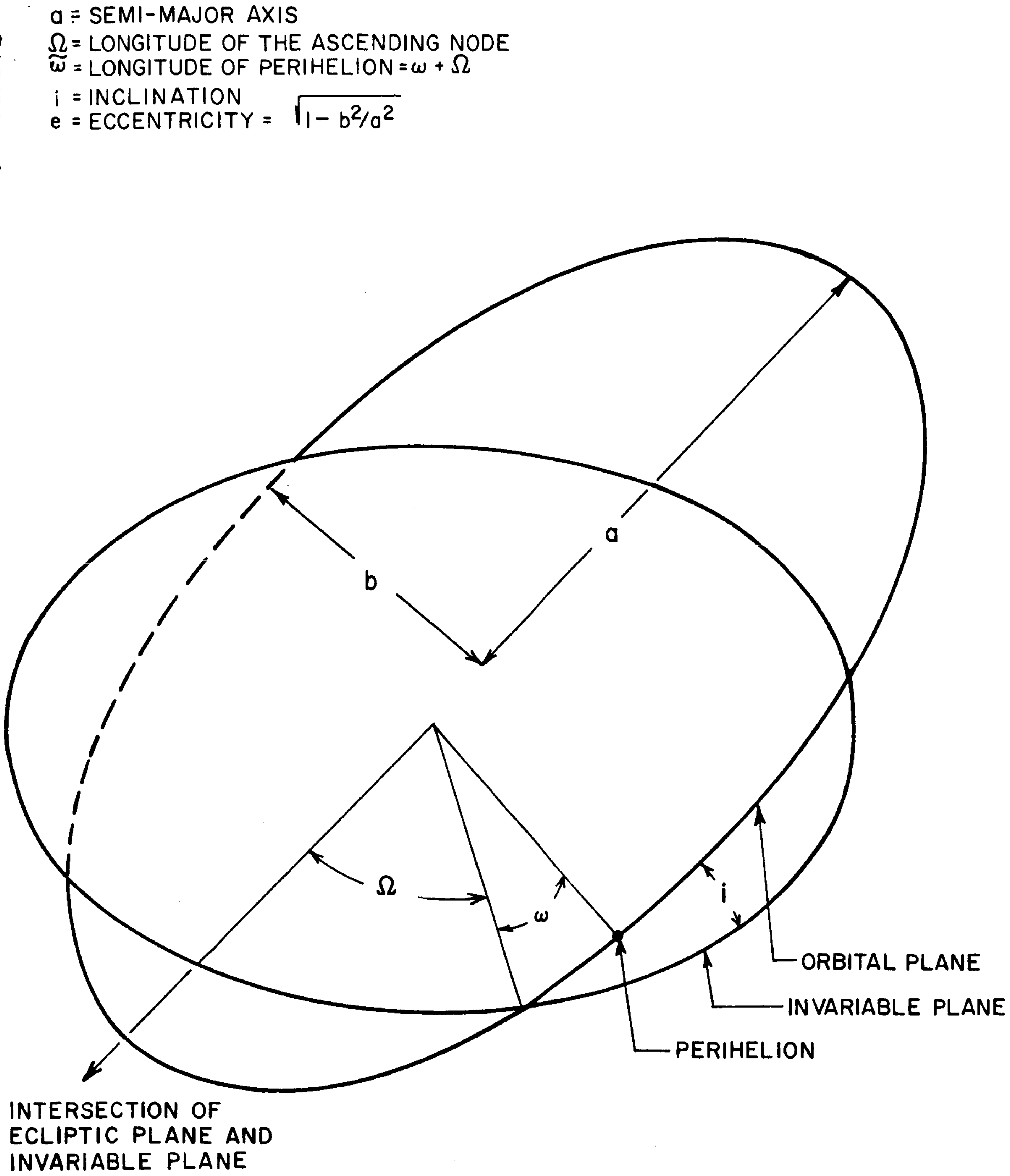
2.3.1 Orbital Elements of the Planets and Asteroids

The planets are nearly coplanar and all move in the same direction in nearly circular orbits about the Sun. This similarity among the planets' motions form a striking regularity which has a minute probability of being a chance arrangement. Thus, the orbital regularities were present at the origin of the solar system, or evolved naturally, and are a boundary condition for theories of the origin and evolution of the solar system. In this section the regularities are treated independently of any theories. The question of whether they were present at solar system origin or are evolutionary is discussed.

2.3.1.1 Orbital Regularities

Figure 3 shows the orbit of a body about the Sun. The orbital elements which are considered here are the inclination i, the eccentricity e, the semi-major axis a, the longitude of ascending node Ω, and the longitude of perihelion $\tilde{\omega}$. The elements i, Ω, and $\tilde{\omega}$ depend on the plane to which the orbital plane is referred, and on an arbitrary but fixed direction in space, which sets the zero of the longitude of ascending node.

It is usual to refer orbital elements to the ecliptic plane and the direction of the vernal equinox (1950). However, the inclination, longitude of ascending node, and longitude of perihelion of an individual planetary orbit can be related to



ure 3. <u>ORBITAL ELEMENTS OF THE PLANETS</u>. The diagram is schematic, in that the perihelion position shown is offset from its actual position for clarity in presenting the definitions of the orbital elements.

a physically more meaningful plane, the invariable plane of the solar system, which is defined as a plane perpendicular to the total angular momentum of the solar system, passing through the system's mass center. The ecliptic plane changes its orientation with respect to the fixed stars in relatively short periods of time; the invariable plane is much more stable, because it can change only if torques are applied to the solar system as a whole. Helpful transformations can be found in Gurnette and Woolley (1961).

As shown in Figure 3 we refer orbital elements to the invariable plane of the solar system, and take the reference direction to be along the line of intersection between the ecliptic plane and the invariable plane. The direction of the line is chosen such that $\Omega_{\text{Earth}} = 180°$.

Orbital elements referred to the ecliptic-vernal equinox are given in Allen (1963). These have been transformed to an invariable-plane-line of nodes reference to make up the list of orbital elements for each planet (an average for the asteroids where meaningful), Table 1. Because of a wide variation in their orbital elements, comets are not considered here.

Comparisons of the orbital elements of the planets are shown in Figures 4 through 7. The accuracy of all orbital elements is very good; spreads in asteroidal elements reflect differences among individual asteroids, and not observational error.

Table 1

ORBITAL ELEMENTS OF PLANETS AND ASTEROIDS WITH RESPECT TO THE INVARIABLE PLANE

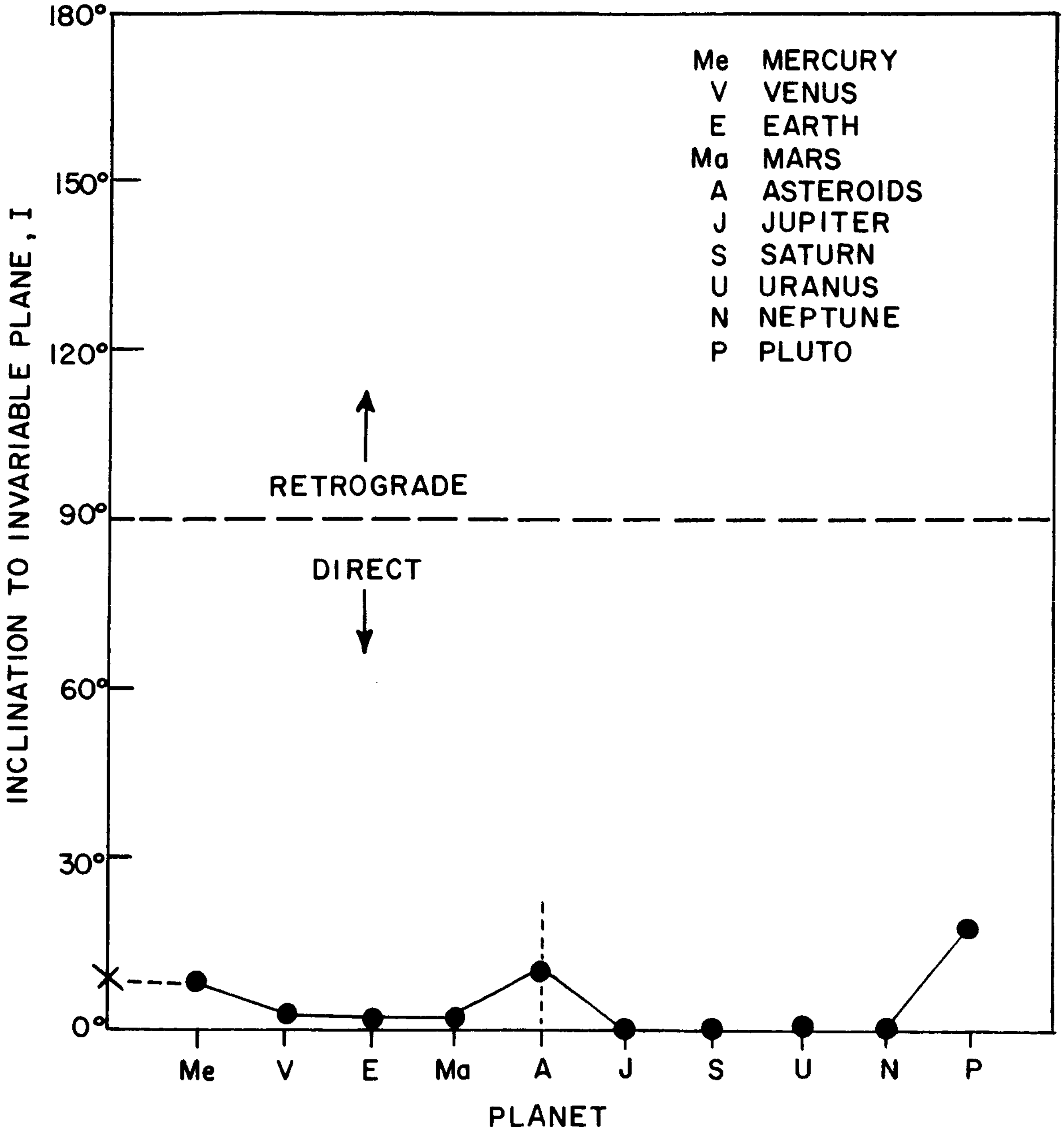
Planet	Inclination to Invariable Plane i	Eccentricity e	Semi-major Axis of Orbit a	Mean Longitude of Ascending Node Ω	Mean Longitude of Perihelion ϖ
Mercury	6.33°	0.206	0.387 AU	287.6°	329.5°
Venus	2.15	0.007	0.723	305.8	23.7
Earth	1.65	0.017	1.000	180.0	355.
Mars	1.71	0.093	1.524	246.8	207.9
Asteroids	8.6	0.14+	2.77*	--	--
Jupiter	0.39	0.048	5.203	240.9	266.3
Saturn	0.87	0.056	9.540	17.5	344.8
Uranus	1.09	0.047	19.18	203.0	62.6
Neptune	0.72	0.008	30.07	92.5	297.0
Pluto	15.52	0.249	39.44	2.7	116.8

* Mean value listed in Allen (1963).

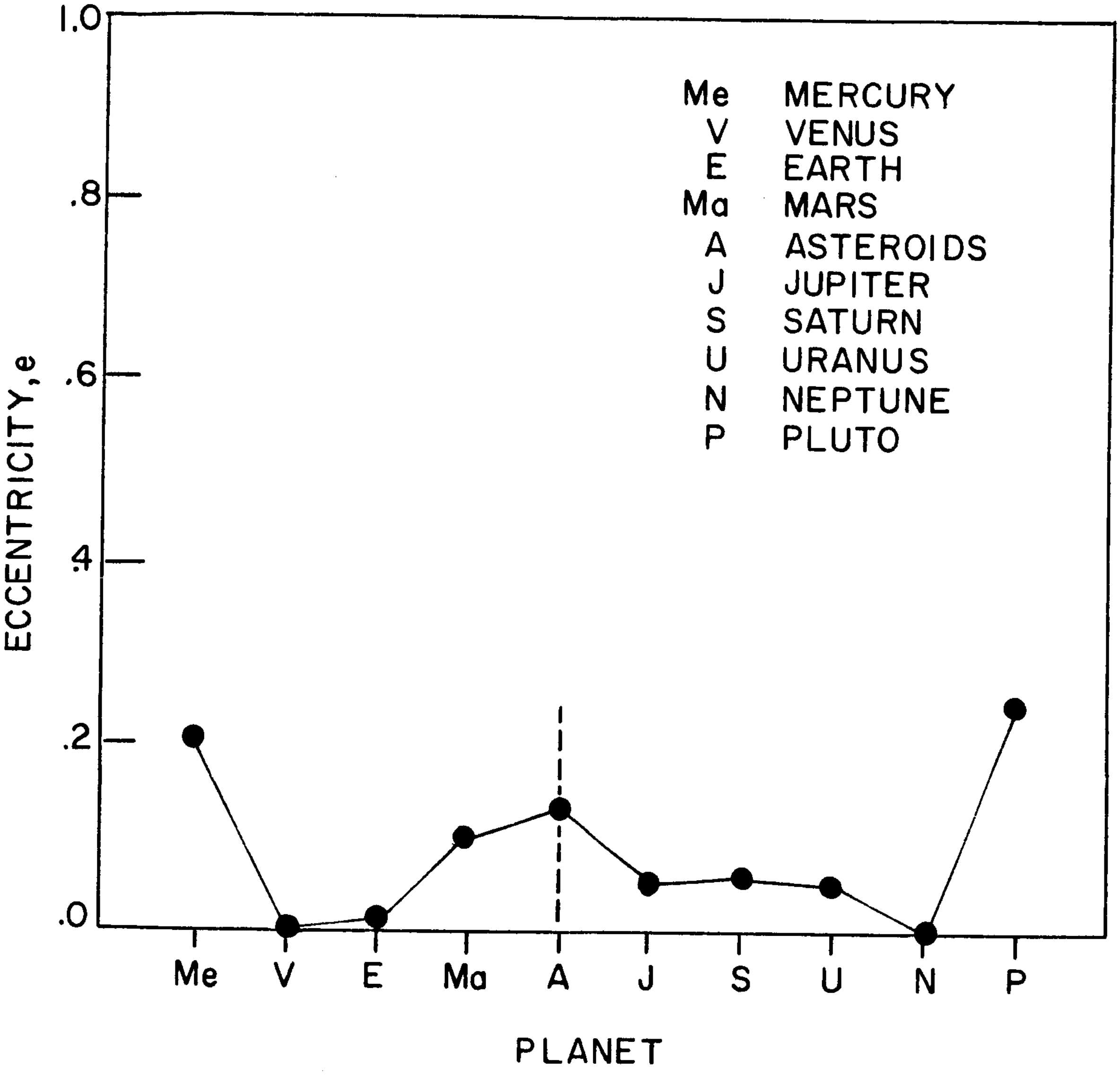
\+ Median value listed in Allen (1963).

The inclinations with respect to the invariable plane of the solar system are shown in Figure 4. The asteroids have a range of inclinations which is indicated by a dashed line. The median value of asteroidal inclination is shown as a dot. By convention, a distinction between direct and retro-grade orbits is made in specifying inclination. Inclinations between 90° and 180° indicate a retrograde orbit, and the total range of possible inclination is 0°-180°. A regularity is apparent from Figure 4. All inclinations are close to 0°. Thus, the planets and asteroids all move around the Sun in the same direction and lie nearly in a plane. The Jovian planets are seen to have especially low inclinations. The choice of the invariable plane as a reference forces some suitable average of the inclinations of the Jovian planets to be low, because almost all (99%) of the solar system's angular momentum is invested in the orbital motion of the Jovian planets. That <u>all</u> of the Jovian planets have extremely low inclination is significant.

Figure 5 shows the orbital eccentricities of the planets and the median asteroid. The dashed line again shows the spread of values for the asteroids. Any eccentricity from 0 to 1 is allowed for an elliptical orbit. The fact that all the eccentricities are quite low indicates that all the planetary orbits are nearly circular. This solar system regularity is a boundary condition on the origin and evolution of the solar system. A second regularity seems to arise for the Jovian planets. Except



gure 4. INCLINATIONS OF THE PLANETS AND ASTEROIDS. The reference plane is the invariable plane of the solar system. Retrograde orbits (by definition) have inclinations between 90° and 180°. The "X" shows the inclination of the solar equatorial plane. Spread of asteroidal inclinations is shown as a dashed line, the median asteroidal inclination as a point.



ure 5. <u>ECCENTRICITIES OF THE PLANETS AND ASTEROIDS</u>. Spread of asteroidal eccentricities is shown as a dashed line, the median asteroidal eccentricity as a point.

for Neptune, the eccentricities lie between 0.047 and 0.056. This similarity in a non-zero but low eccentricity may also be a solar system regularity, though the sample is so small that it may be due to chance.

Titius proposed, and Bode promulgated, a "law" (the Titius-Bode law) to empirically relate planetary semi-major axes to "planetary number". This has usually been considered to be a boundary condition on theories of the origin and evolution of the solar system. One form of the law is as follows:

$$a_n = c_1 + c_2(x)^n ,$$

where a_n is the semi-major axis of the orbit of nth planet, c_1, c_2, and x are constants determined empirically, and n is the planetary number taken as:

$n = -\infty$ for Mercury
$= 0$ for Venus
$= 1$ for Earth
$= 2$ for Mars
$= 3$ for the mean asteroid
$= 4$ for Jupiter,
etc.

Values for the constants are:

$c_1 = 0.4$ AU
$c_2 = 0.3$ AU
$x = 2.0$.

Figure 6 displays planetary and asteroid semi-major axes in a form designed to best check the accuracy of the

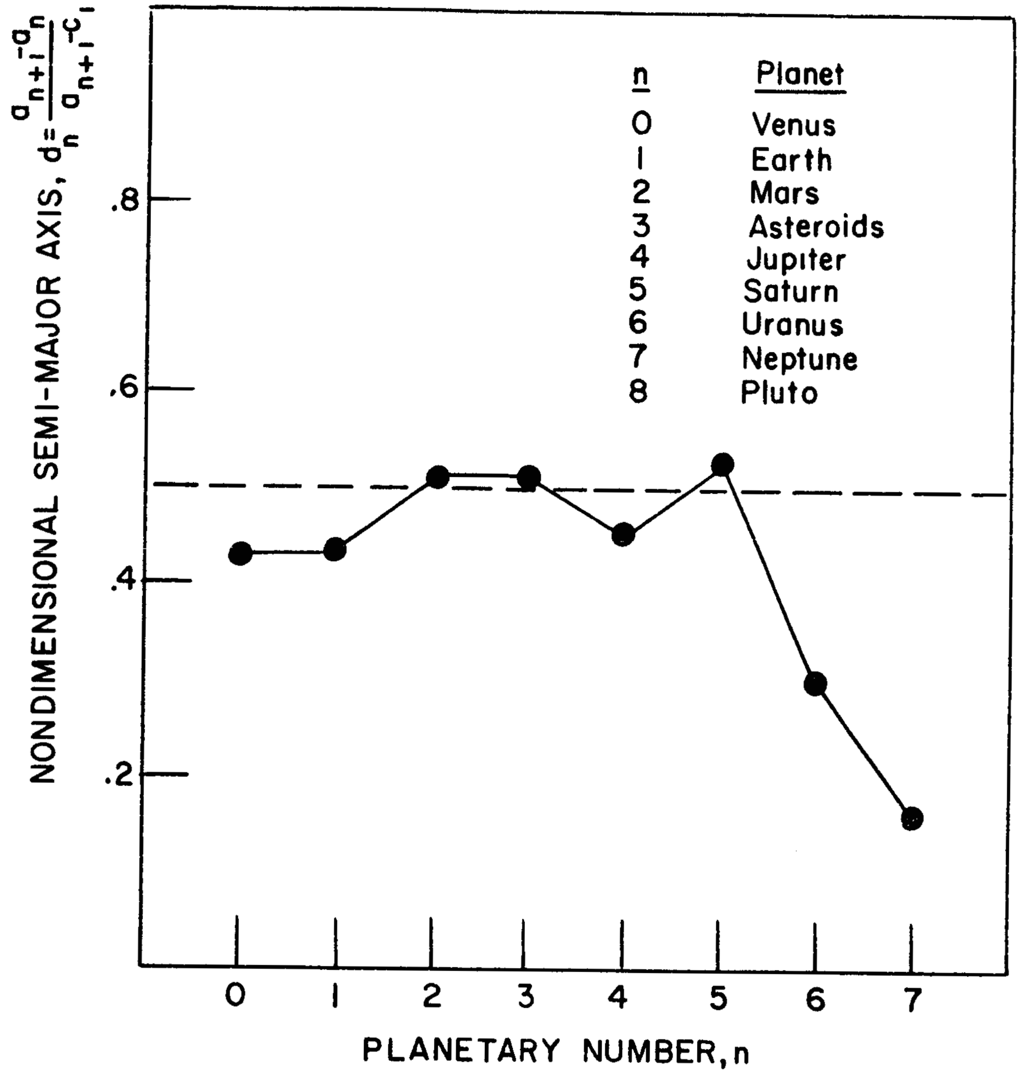


Figure 6. COMPARISON OF THE SEMI-MAJOR AXES OF ADJACENT PLANETS AND THE MEAN ASTEROID. The parameter c_1 is found empirically to be .4 AU for best fit. A point having n as abscissa compares the semi-major axis of the nth planet with that of the (n+1)st planet.

Titius-Bode law's correlations. Since the planets are already ordered in ascending distance from the Sun, it follows that the (n+1)st planet has a larger semi-major axis than the nth planet. To compare observations with the content of Bode's law, it is desirable to compare semi-major axis of adjacent planets, and to normalize in some fashion. If we form the quantity:

$$d_n = \frac{a_{n+1} - a_n}{a_{n+1} - c_1},$$

d_n has the following properties:

1) It compares the distances of the semi-major axes of adjacent planets
2) It is nondimensional (normalized)
3) Its value can range only from 0 to 1 for $n > 0$, and
4) The Titius-Bode law predicts that d_n is independent of n for $n > 0$, and is equal to $(x-1)/x$.

In Figure 6, d_n is plotted against n over the range $n = 0$ to $n = 7$ ($n = 0$ compares the semi-major axis of Earth to that of Venus; $n = 7$ compares Pluto to Neptune). The law is seen to hold fairly well, indicating some regularity. It should be emphasized that the Titius-Bode law itself has some undesirable properties:

1) Mercury must be treated separately in that its planetary number is assigned as $n = -\infty$, a discontinuity in the sequence of other planetary numbers (...4, 3, 2, 1, 0, ...).

2) Three constants appear which must be evaluated empirically from only ten data points.

3) The asteroids count as exactly 1 planet, even though they are very numerous, and have, in total, a mass even less than that of Mercury.

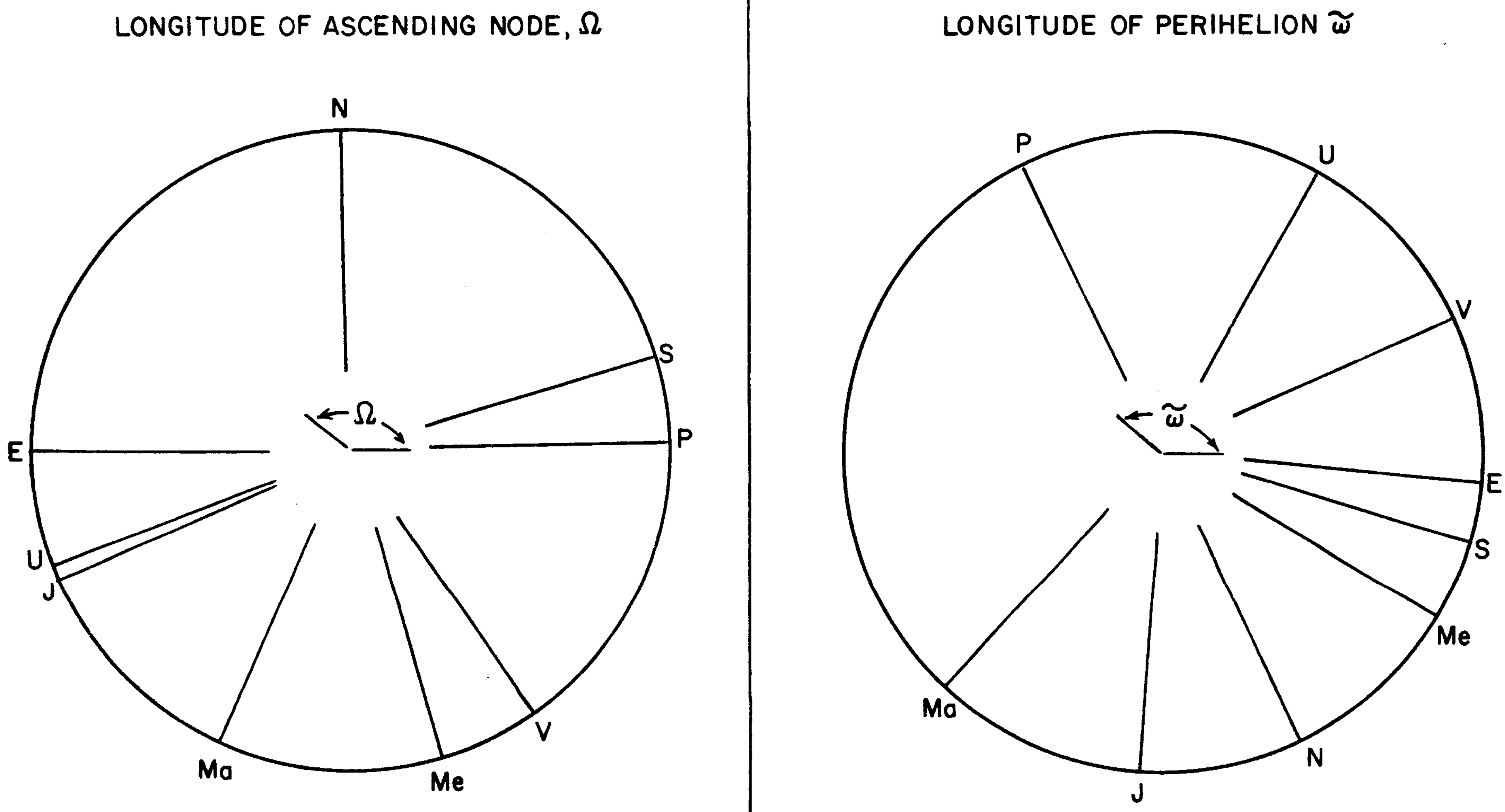
Therefore, though there is some regularity in the semi-major axes of the planets in that they follow (with considerable scatter) the Titius-Bode law, the regularity is not particularly strong.

In Figure 7 the longitude of ascending node Ω and the longitude of perihelion $\tilde{\omega}$ is shown for each planet. A regularity would exist if values of Ω and $\tilde{\omega}$ were markedly clustered. Since there is no marked clustering, it is clear that any regularity in these elements is small and presumably of minor importance.

The following boundary conditions are thus imposed on a theory of the origin and evolution of the solar system:

> THE INCLINATIONS AND ECCENTRICITIES OF THE PLANETS AND ASTEROIDS ARE <u>VERY LOW</u>; THEIR ORBITAL RADII FOLLOW AN EMPIRICAL LAW (BODE'S LAW) APPROXIMATELY.

One other interesting feature is apparent from Figures 4 through 6. The orbital elements of Mercury, Mars, the asteroids and Pluto are the least regular in the solar system, and those of Jupiter, Saturn, and Uranus are the most regular. Pluto and Mercury are definitely the most irregular,


LONGITUDE OF ASCENDING NODE, Ω

LONGITUDE OF PERIHELION $\tilde{\omega}$

Figure 7. LONGITUDES OF ASCENDING NODE AND PERIHELION OF THE PLANETS. The reference plane is the invariable plane of the solar system. The reference direction points toward Earth's descending node. The longitudes are measured from 0° (horizontal to the right) counter-clockwise.

and they are farthest from 10 AU. Mars and the asteroids have very low mass. On the other hand, the orbital elements of the large, centrally located planets (Jupiter, Saturn, Uranus) show the most regularity. Empirically, the least regular planets with respect to their orbital elements are the lightest ones, and/or those having orbits farthest from about 10 AU. The numbers of planets on which these relationships appear are so small, however, that they could be chance arrangements.

We now ask whether the orbital regularities are boundary conditions of solar system origin, or are evolutionary. Whipple (1963) succinctly states the question:

> We notice next that the orbits lie almost in a plane, very close to the ecliptic, the plane of the Earth's orbit about the Sun. This favoritism on the part of the planets in adopting a common plane of motion is probably not due to chance. Although no rigorous proof has been given, it is possible that Jupiter is responsible, because this planet is 317 times as massive as the Earth and possesses 0.7 of the combined mass of all the planets. Jupiter is certainly the master planet and by gravitational attraction may have regulated the orbits of the others. There is the more likely possibility, of course, that the planets were all formed in a plane - but we must investigate this matter later on.

As part of this program, a study of planetary perturbations aimed at the stability of possible "original" orbital elements has been undertaken. Simplifications are necessary. In particular, we considered the secular perturbation of a small planet by a massive planet like Jupiter. The results are the following: The semi-major axis is invariant. The result of secular perturbation theory carried to the second order in the "smallness" parameters which are taken to be the eccentricity and inclination of both Jupiter and the perturbed body is that the inclination and eccentricity of the small body are unchanged. More sophisticated theory is required to go to higher order. For a circular Jupiter orbit, Kozai (1962) has shown analytically that the inclination and eccentricity undergo periodic oscillation. Numerical work carried out by the author yields the same result obtained by Kozai, and also indicates that the bounds on e and i are quite narrow for typical planetary semi-major axes, regardless of the other orbital elements. For an elliptical Jupiter orbit, numerical calculations indicate non-periodic behavior of e and i, though they still appear bounded within fairly narrow limits.

Another kind of perturbation has been studied in which either the mass of the Sun or a planet changes in time, e.g., either by accretion or by atmospheric escape. Possible secular changes in the gravitational constant are also included. The result of this study is that, if the time taken for significant mass or gravitational constant changes is long compared with the orbital period, then only the semi-major axis changes in time, while the other orbital elements remain fixed.

Looking at the solar system as a whole, it is likely that the long-term effect of perturbations is to leave the inclination and the eccentricity relatively fixed, allowing the semi-major axis to change somewhat by slow processes of accretion and depletion.

The overall conclusion is, then, that the boundary condition of small inclinations and eccentricities and regularity in semi-major axes cited earlier are probably boundary conditions on the theories of the origin rather than of the evolution of the solar system.

2.3.2 Orbital Elements of Planetary Satellites

Striking orbital regularities are found in a majority of planetary satellites. They are the same regularities as for the planets themselves - low inclinations and eccentricities and a modest fit to a "Titius-Bode law". Here also, there appears to be far too much order to be explainable by chance.

Although theories for origin and evolution of the solar system tend to concentrate more on the planets than on satellite systems around planets, a discussion of the orbital elements of the satellites is relevant, because the Sun's planetary system and a planet's satellite system may have been formed in a similar fashion (see Brandt and Hodge 1964, Kuiper undated).

Table 2, which lists the mean orbital distance, inclination to the planetary equator, and eccentricity of all known satellites, has been constructed from data found in Allen (1963) and Gurnette and Woolley (1961). The satellites fall naturally into two distinct classes and have been split

Table 2

SATELLITE ORBITS

		Mean Distance (10^3 km)	Inclination of Orbit to Planet's Equator		Eccentricity of Mean Orbit
		Class 1 - Regular Satellites			
Mars					
I	Phobos	9.4	0°	57′	0.0210
II	Diemos	23.5	1	18	0.0028
Jupiter					
V		181	0	24	0.003
I	Io	422	0		0
II	Europa	671	0		0
III	Ganymede	1071	0		0
IV	Callisto	1884	0		0
Saturn					
I	Mimas	186	1	31	0.0201
II	Enceladus	238	0	01	0.00444
III	Tethys	295	1	06	0
IV	Dione	378	0	01	0.00221
V	Rhea	527	0	21	0.00098
VI	Titan	1222	0	20	0.0289
VII	Hyperion	1481	0	26	0.104
Uranus					
V	Miranda	124	0		< 0.01
I	Ariel	192	0		0.0028
II	Umbriel	267	0		0.0035
III	Titania	438	0		0.0024
IV	Oberon	587	0		0.0007
		Class 2 - Irregular Satellites			
Earth					
	Moon	384.4	Var.		0.05490
Jupiter					
VI		11480	27°	38′	0.15798
VII		11740	24	46	0.20719
X		11860	29	01	0.13029
XII		21200	147		0.16870
XI		22600	164		0.20678
VIII		23500	145		0.378
IX		23700	153		0.275
Saturn					
VIII	Iapetus	3562	14	43	0.02828
IX	Phoebe	12960	150		0.16326
Neptune					
I	Triton	354	159	57	0
II	Nereid	5570	27	27	0.76

up in Table 2. In one class are the "regular" satellites, whose orbital inclinations referred to the equatorial plane of the parent planet are extremely low, less than 1.6°.* In addition, the eccentricities of "regular" satellites are very low.

The second class are the "irregular" satellites having much higher inclinations referred to the equatorial plane of the parent planet, in no case being less than 14°. This definite gap in inclinations, from 1.6° to 14° permits unambiguous classification of each satellite. The irregular satellites also tend to have moderately large eccentricities. Most think that these irregular satellites are captured asteroids and, as such, are not relevant to the origin of the solar system, nor are they particularly important for understanding its evolution.

As is shown in Table 2, the inclinations and eccentricities of regular satellites are even lower than the inclinations and eccentricities of the planets. These direct, coplanar, and circular orbits are certainly a regularity.

Three planets, Jupiter, Saturn, and Uranus have enough regular satellites to consider a "satellite Titius-Bode law". The law is of the form:

$$a_n = c_1 + c_2 x^n$$

---

*It should be mentioned here that the equatorial plane is very nearly the invariable plane of the system (parent planet plus satellites). The reason is that the parent's spin angular momentum is very much greater than the orbital angular momenta of the satellites. This differs from the solar system as a whole, where the Sun's spin angular momentum is small, only 2% of the total. As is shown by the "X" in Figure 3, the Sun's equator is inclined at 7° to the invariable plane.

where a_n is the semi-major axis of the nth satellite ($n = -\infty$, 0, 1, ...) and c_1, c_2, and x are constants for a given satellite system. Approximate fits to the first three satellites of each system are used to evaluate these constants:

	c_1	c_2	x
Jupiter	2.6	3.4	2
Saturn	2.75	1.4	1.72
Uranus	Deleted	6.15	1.50

In the case of Uranus, a good fit occurs if the c_1 is set to zero, and the closest satellite is given a "satellite number" of 0, instead of $-\infty$.

Figure 8 displays d_n as a function of n, where d_n is again defined as:

$$d_n = \frac{a_{n+1} - a_n}{a_{n+1} - c_1} .$$

The first point on each curve is guaranteed to lie on or near the predictions of the "satellite Titius-Bode law" because it is used to evaluate the constant x, which solely determines the position of the dashed line. Therefore, the first point should be ignored in seeing how well the law is followed. The predicted points number 2 for Jupiter, 4 for Saturn, and 3 for Uranus.

As can be seen from Figure 8, the law works fairly well in the case of Jupiter's satellites, less well for Uranus', and not at all well for Saturn's, though the numbers of predicted points are so small that drawing firm conclusions is

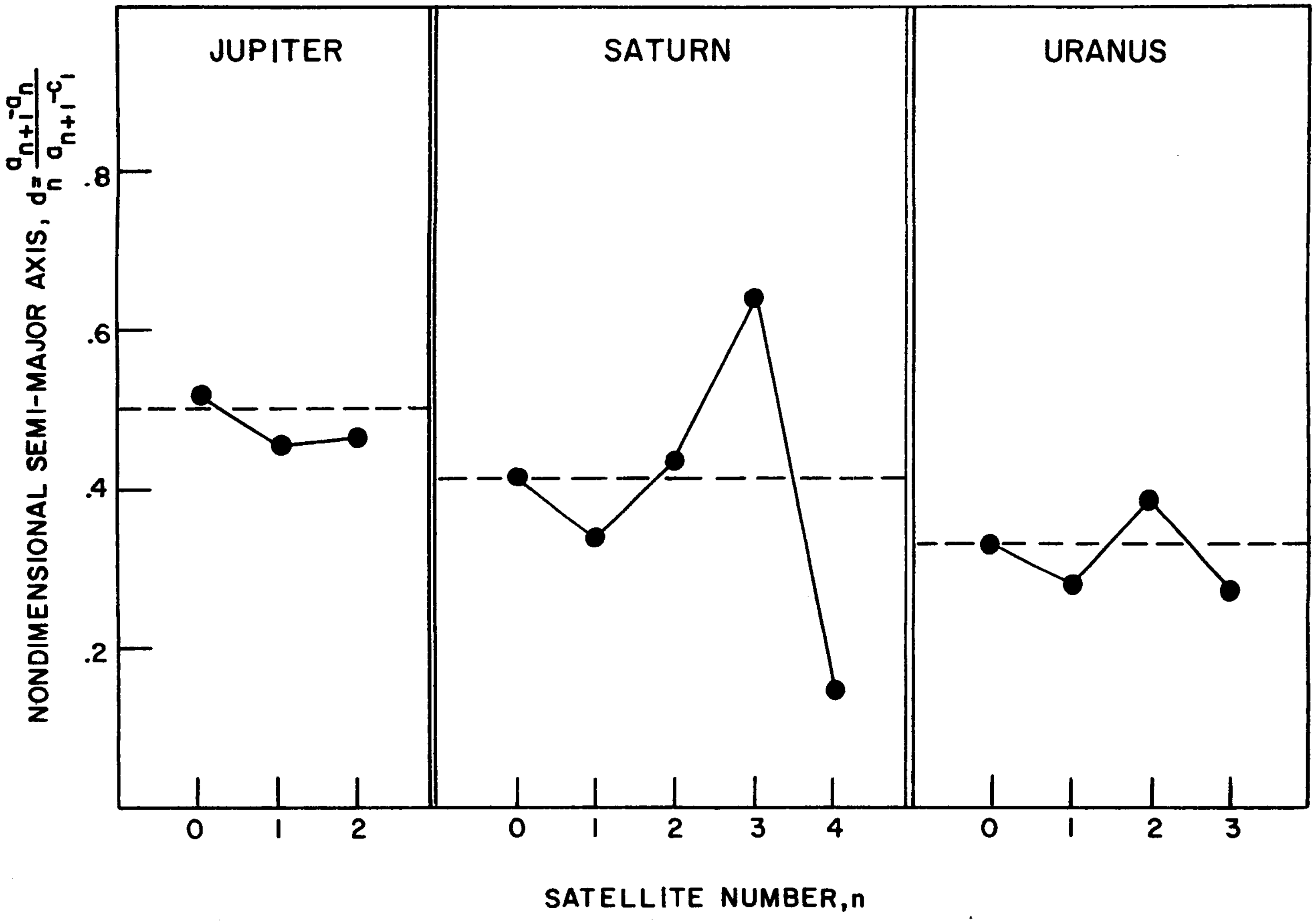


Figure 8. RELATIVE SEMI-MAJOR AXES OF REGULAR SATELLITES. The parameter c_1 (different for each satellite system) is chosen to best fit a "satellite Titius-Bode law". a_n is the semi-major axis of the orbit of the nth satellite. $n = -\infty$ for the innermost satellite of Jupiter and Saturn; $n = 0$ for the innermost satellite of Uranus. The satellite numbers are ordered by ascending semi-major axes. The dashed lines show the predictions of "satellite Titius-Bode laws".

risky. If anything, possible regularities in satellite semi-major axes are weak, even weaker than in planetary semi-major axes.

The boundary condition on theories of the origin and evolution of the solar system is, then:

> REGULAR SATELLITES HAVE EXTREMELY LOW INCLINATIONS AND ECCENTRICITIES; THEIR ORBITAL RADII FOLLOW A "BODE'S LAW" LESS WELL THAN DO THE PLANETS.

The influence of this boundary condition for the solar system as a whole is, then:

(1) The very low orbital inclinations and eccentricities of regular satellites enhances the importance of low planetary eccentricities and inclinations as boundary conditions for theories of the origin of the solar system.

(2) The somewhat larger deviations from a Titius-Bode law by satellites than by planets reduces the importance of the planetary Titius-Bode law as a boundary condition for theories of the origin and evolution of the solar system.

2.3.3 Boundary Conditions from Rotations

In this section the rotation of the planets is treated. Although the origin of planetary magnetic fields is not really known, most theories involve planetary rotation. For this reason, magnetic fields are also considered in this section.

The planets, except for Venus and Pluto, are known to rotate in a forward sense (spin angular momentum adds to orbital angular momentum), and almost all planets and asteroids having known periods rotate once in several hours.

These regularities, especially the rotation period similarity, cannot be due to chance, and are boundary conditions for the origin and evolution of the solar system.

Table 3 lists the best values known at present for the sidereal rotation rates of the planets and the Sun. The inclinations of the planetary equator referred to its orbital plane (called "obliquity" in this report) and of the Sun's equator to the invariable plane of the solar system are listed. Also included in the table are best current estimates and measurements of planetary magnetic field strengths and orientations.

Figure 9 displays the rotational data. The top half shows the inclinations except for the asteroids and Pluto for which data are not available. The rotational axes of Mercury and Venus, as shown by radar studies, are close to the perpendicular to their orbital plane. Venus, however, rotates in a retrograde sense (spin angular momentum vector opposite to its orbital angular momentum) (Pettengill and Shapiro 1965), leading to values of obliquity near 180°. In the case of Uranus, the rotational axis lies almost in the plane of its orbit, resulting in an obliquity of nearly 90°.

The lower half of Figure 9 shows the sidereal rotation period for each planet. The value of some six days for Pluto is open to question, and the values for Mercury and

Table 3

PLANETARY ROTATION AND MAGNETIC FIELD

	Rotation Speed (sidereal)	Inclination of Equator to Orbit	Magnetic Field at Surface	Inclination of Magnetic Equator to Equator
Sun	27 days	7° (1)	Variable (0-5000 gauss)	Variable (all)
Mercury	55 ± 5 days (2)	Low (2)	?	?
Venus	242.6 ± 0.6 days (3)	~180° (3)	0.3 gauss (4)	?
Earth	$23^h 56^m 4^s$ (1)	23° (1)	.5 gauss (4)	5° (4)
Mars	$24^h 37^m 22^s$ (1)	24° (1)	.001 gauss (5)	?
Asteroids	5-18 hours (1)	--	?	?
Jupiter	$9^h 50\text{-}55^m$ (1)	3° (1)	5-5000 gauss (6)	9° (7)
Saturn	$10^h 14\text{-}38^m$ (1)	27° (1)	?	?
Uranus	$10^h 49^m$ (1)	98° (1)	?	?
Neptune	15^h (1)	29° (1)	?	?
Pluto	6.7 days? (1)	?	?	?

References:
(1) Allen (1963)
(2) Pettergill and Shapiro (1965)
(3) Goldstein (1966)
(4) Brandt and Hodge (1964)
(5) Fawcett et al. (1965)
(6) Witting et al. (1965)
(7) Morris and Berge (1962)

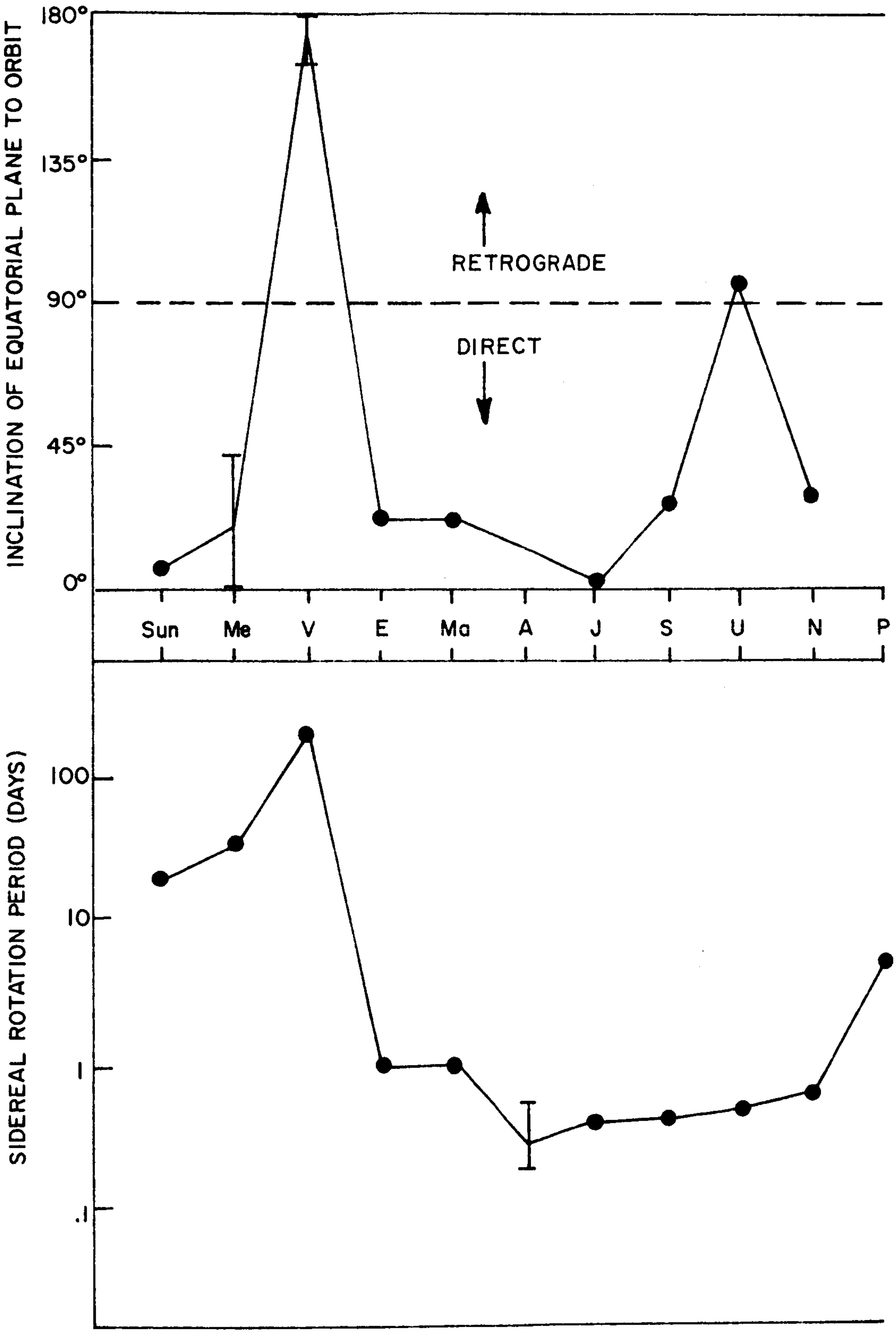


Figure 9. ROTATIONS OF THE SUN, PLANETS, AND ASTEROIDS. The error bars on asteroidal rotation periods indicate the spread of values for various asteroids; the other error bars indicate experimental uncertainty. Data are taken from Allen (1962), except for Mercury and Venus, where latest radar measurements are given.

Venus have a considerable spread. Rotation periods of a number of asteroids have been measured in photoelectric studies of fluctuations in the reflected sunlight. Resulting rotation periods range from 5^h16^m (Eros) to possibly as large as 18^h (Hygiea).

The inclination between the equatorial plane of a planet and its orbital plane is usually moderately low, $\sim 25°$, although a couple of glaring exceptions exist (Venus and Uranus). The tendency of planets to have low rotational inclinations forms a regularity, but a much weaker one than the regularity associated with the very low inclinations of the orbits themselves to the invariable plane of the solar system. The retrograde spin of Venus seems difficult to explain.

On the other hand, the rotation periods show surprising regularity. In the case of the planets between Earth and Neptune the rotation periods, even including asteroids, differ by no more than a factor of five. (Mercury and Venus may have had substantially higher rotational speeds in the past which have been reduced by tidal forces by the Sun.) This factor of five difference in an intrinsic property of solar system bodies is markedly lower than the differences in other intrinsic properties of the same bodies, such as mass, radius, etc. which are many orders of magnitude. To sum up, the following are boundary conditions to the origin and evolution of the solar system:

THE PLANETS AND ASTEROIDS ROTATE WITH SMALL VARIATIONS IN PERIOD, EXCEPT FOR VENUS, MERCURY AND PLUTO; THEY TEND TO HAVE FAIRLY LOW OBLIQUITY.

The question of the long-term stability of rotation rates can be asked, to see whether the rotation regularities now observed were present at the solar system's origin. The answer is not clear at present. Certainly changes in a satellite's semi-major axis due to tidal forces will change the primary's rotation rate. Except for the Earth-Moon system, however, resulting changes in rotation rate are very small, because the masses of all satellites except Moon are very small compared to the masses of the primaries ($<2 \times 10^{-4}$). Solar torques can lead to changes of a planet's angular momentum. If the planet is a rigid body, the magnitude of the angular momentum is invariant, however. The major unanswered question is the response of a planet with an extensive fluid core, surface, or atmosphere to solar torques over the five billion year lifetime of the solar system. Until this is answered, one cannot ascertain whether the regularity in planetary rotation rates is evolutionary or was present immediately after the origin of the solar system.

As can be seen from Table 3, our present knowledge of planetary magnetic fields is quite scanty. The Earth and Jupiter have substantial surface magnetic fields, the Sun has a very low field for its size ($\sim$1 gauss), and Venus and Mars have very small surface magnetic fields, if any. There is essentially no information regarding the magnetic orientation or field strength of other planets.*

It is not clear at this time whether a planet's magnetic moment preserves some clues to the origin and/or evolution of the solar system, e.g., its thermal history, or whether it is merely a function of other planetary parameters such as size, spin, electrical conductivity, etc. Much additional basic observational evidence is probably required before the relevance of planetary magnetic fields to solar system origin and evolution can be determined. The magnetic moment is most easily determined and can be obtained to first order from flyby missions. Variations in the field strength and its orientation over very long periods are also of interest but will probably require lander missions.

2.4 Physical and Chemical Properties

2.4.1 Overall Solar System Density

Table 4 lists the masses and semi-major axes of the planets, excluding Pluto, whose mass is unknown. The values shown are taken from Allen (1963). One parameter of interest is the present spatial distribution of solar system matter. This acts as a significant boundary condition if planets form out of a single cloud of gas or dust. Of course, most of the matter in the solar system is now found lumped in the Sun, planets or asteroids. In order to smooth out a solar system density distribution, we take all the mass of a planet and spread it uniformly between spherical shells located at the mid-point distance

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*Nonthermal radio emission from Saturn has been reported, which would indicate the presence of a magnetic field. It now appears that these results are spurious, and that only thermal radio emission from Saturn has been detected.

Table 4

MASSES AND SEMI-MAJOR AXES OF PLANETS

Planet	Mass (in Earth masses)	Semi-Major Axes (AU)	Solar System Density* (m_o/AU^3)
Mercury	.054	.387	.85
Venus	.815	.723	2.7
Earth	1.000	1.000	1.5
Mars	.108	1.524	.05
Asteroids	.1	2.4	.03
Jupiter	318	5.203	2.4
Saturn	95.2	9.540	.15
Uranus	14.5	19.18	.03
Neptune	17.2	30.07	.01

*Defined as the mass of the planets divided by the volume between the spherical shells of radii 1/2 $(a_n + a_{n+1})$ and 1/2 $(a_n + a_{n-1})$ where a_n is the semi-major axis of the planet in question and a_{n+1} is the semi-major axis of the planet adjacent to the planet in question.

between the given planet and its nearest neighbors. In this way it is possible to convert the mass data shown in Table 4 to a density histogram - Figure 10, which is a plot of this distributed density of matter in the solar system versus distance from the Sun.

The choice of three-dimensional geometry (spherical shells, as opposed to segments of a disk) is arbitrary, as is the inclusion of the asteroids as a separate object. Nevertheless, the overall shape of the curve does not change if two-dimensional geometry is adopted, or if the asteroids are ignored, combined with Mars, or combined with Jupiter. In particular, the region near Mars and the asteroids is much less dense than the region near Jupiter. A boundary condition to the origin and evolution of the solar system is, therefore;

THE DISTRIBUTION OF MATTER BETWEEN EARTH AND JUPITER.

It is interesting to note that the asteroids exist at the only nearby place in the solar system so undense that small bodies would not rapidly be captured by a planet.

2.4.2 Differences Between Jovian and Terrestrial Planets

The Jovian planets (Jupiter, Saturn, Uranus, and Neptune) are all massive, low-density, low-molecular-weight planets; the terrestrial planets (Mercury, Venus, Earth and Mars) are all light, high-density, high-molecular-weight planets. Similarities and dissimilarities in these gross physical characteristics are related to solar system origin and evolution.

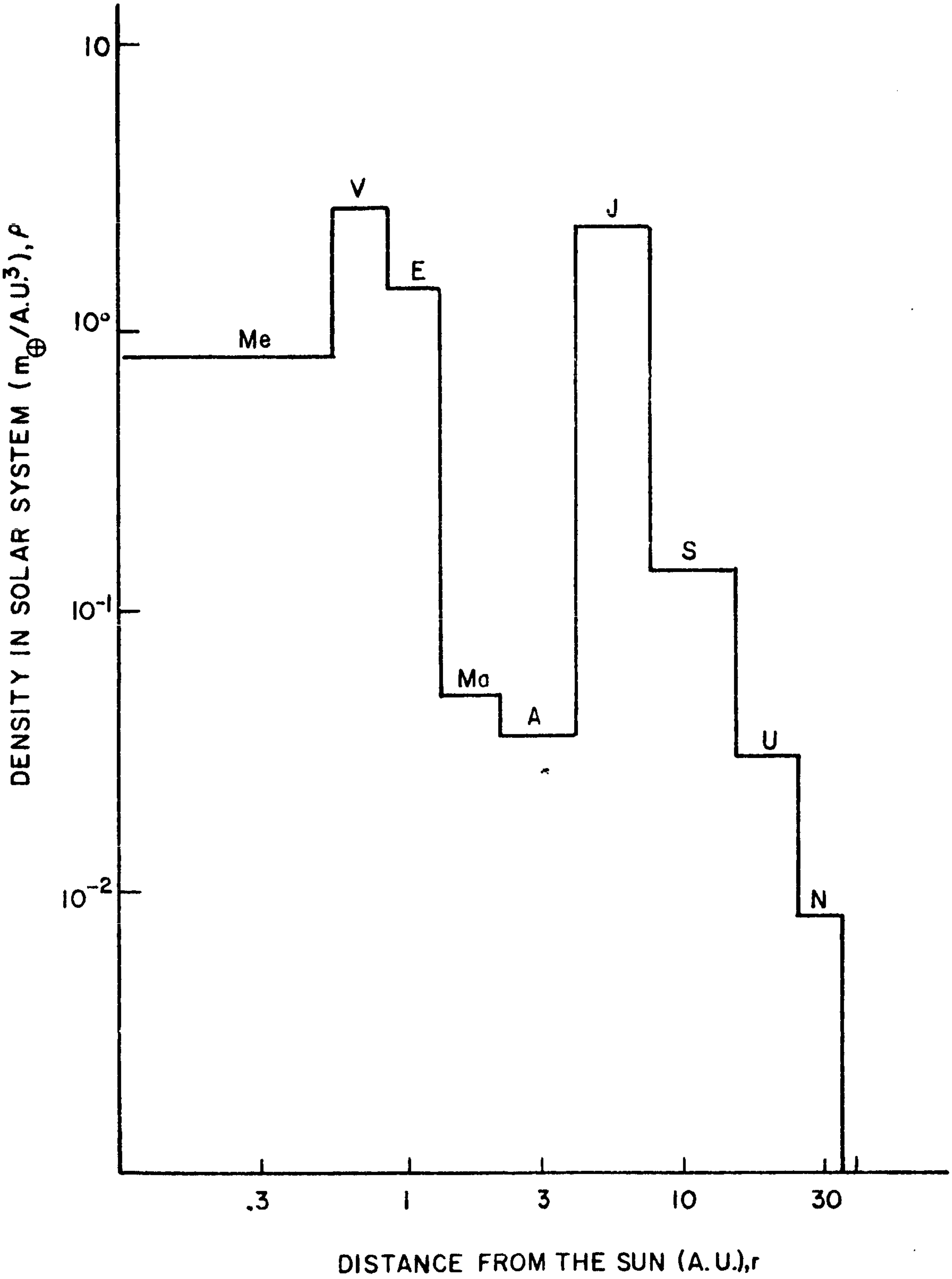


Figure 10. DENSITY OF MATTER IN THE SOLAR SYSTEM. The mass of each planet is spread uniformly between spherical shells located midway between the planet and its nearest neighbors.

In Table 5 the gross physical properties of the planets are summarized (Pluto's properties are so poorly known that it is ignored here). The values of planetary density shown are taken from Allen (1963). They are determined by comparing the size of the planet (not too well determined) to the mass of the planet (usually well determined). Table 5 also lists planetary blackbody temperatures. A planet without internal heat sources in thermal equilibrium must radiate as much energy (mostly in the infrared) as it receives from the Sun (mostly in the visible). The balance is achieved by the planet's arriving at a temperature at which the planet radiates as much energy as it receives.

Blanco and McCluskey(1961) give values for the temperature of each planet, using the measured visible albedo, and perfect emissivity in the infrared (the "blackbody" temperature). These temperatures are given in Table 5.

A rough indication of the composition of the planets, as given by Whipple (1963), is included in Table 5. He splits the kinds of material into three types: earthy, icy, and gaseous. The earthy type includes lithium, magnesium, iron and many others, as well as their compounds (silicates, oxides, etc.). The icy materials include carbon, nitrogen, oxygen as well as their compounds with each other and with hydrogen. The gaseous elements are hydrogen and noble gases.

Knowledge of the chemical composition of the atmospheres of the various planets is poor at present, though improvements

Table 5

GROSS PHYSICAL PROPERTIES OF THE PLANETS

	Density (gm/cm^3)	Blackbody Temperature (°K)	Composition			Mean Molecular Weight of Atmosphere	Critical Molecular Weight (escape in 5 x 10^9 yrs)
			Earthy Fraction	Icy Fraction	Gaseous Fraction		
							(T_{exo} = $6T_{BB}$)
Mercury	5.4	525	1.0	--	--	?	50
Venus	5.1	373	1.0	--	--	28-44	15
Earth	5.52	246	1.0	--	--	29	8
Mars	3.97	218	1.0	--	--	28-44	32
Jupiter	1.334	102	--	.1	.9	2-4	2
Saturn	.684	76	.01	.3	.7	2-4	2
Uranus	1.60	49	.1	.8	.1	2-4	2
Neptune	2.25	40	.2	.7	.1	2-4	2

are being made rapidly. Unfortunately, the abundance of the primary constituent in most planetary atmospheres has not been measured, because the existence of some common gases, such as hydrogen, helium, nitrogen, and argon, cannot be determined from Earth. This accounts for the spread of values shown in the table for mean molecular weight of the planetary atmosphere.

Table 5 also lists the approximate "critical" molecular weight of molecules having an escape time equal to the lifetime of the solar system (about 5 billion years). Only gases having larger molecular weight than the critical molecular weight can have been present on the planet from the time of its origin although they may be present as a result of more recent degassing. By analogy with the Earth, where the exospheric temperature is 1500°K, we have assumed that each planet's exospheric temperature is six times its blackbody temperature. This assumption is questionable since recent work suggests lower exospheric temperatures than shown for Mars and Jupiter. However, some indication of escape since origin is obtained as a result.

There is in Table 5 a similarity in the observed gross physical properties, i.e., mass, density, composition and atmospheric molecular weights among terrestrial planets (Mercury through Mars) and among Jovian planets (Jupiter through Neptune). Further there is a great dissimilarity of the observed gross physical properties of a terrestrial planet and a Jovian planet, leading to the boundary condition:

BASED ON GROSS PHYSICAL PROPERTIES, PLANETS FALL INTO TWO CLASSES, JOVIAN (LARGE, LOW DENSITY, LOW MOLECULAR WEIGHT) AND TERRESTRIAL (SMALL, HIGH DENSITY, HIGH MOLECULAR WEIGHT).

The sharp distinction in physical properties of terrestrial planets compared to Jovian planets may be due to a wide gap in the molecular weight of gases possible at planetary temperatures and pressures, i.e., no gas is possible at high concentration having molecular weight between helium (molecular weight 4), and methane (molecular weight 16). The Jovian planets are cold enough and massive enough to retain hydrogen and helium, and become low density, low molecular weight planets composed mostly of "gaseous" and "icy" constituents. The terrestrial planets were probably too hot and not massive enough to retain hydrogen and helium, and could have evolved to planets of high density, high molecular weights composed mostly of "earthy" materials.

It appears likely, then, that most of the regularities found in the gross physical properties of the planets act as boundary conditions for theories of the evolution of the solar system, but not necessarily of its origin.

2.4.3 Composition of Terrestrial Objects

Meteorites and the crust of the Earth are available for detailed chemical study; some properties of the other terrestrial planets can be inferred from their densities. The idea of formulating a relation between such chemical evidence and questions regarding solar system origin and evolution is due principally to Urey. This idea is a rather recent development, and some of the detailed chemical studies show great diversity; conclusions must, therefore, be drawn very carefully.

As time goes on, it can be expected that chemical evidence will play an increasingly important role in studies of the origin and evolution of the solar system. In this and the next two sections we shall outline some of the less speculative conclusions arrived at from chemical studies, without going into too many of the technical details.

Meteorites fall into two broad classes: "irons," which are composed primarily of iron and nickel, and "stones," which are composed primarily of silicates. Furthermore, it is thought that iron-nickel and/or silicates form the bulk of all terrestrial planets and asteroids.

It is possible to calculate, though not uniquely, an approximate fraction of iron-nickel from the density and size of a terrestrial object (the remainder being silicates). Table 6, taken from Urey (1957) shows the result of such calculations. The uncompressed density is defined as the mean density at zero pressure. Two values for Mercury and Mars are shown, because their radii were uncertain (Mercury's still is).

In Table 6 one can observe a boundary condition on theories of the origin and evolution of the solar system.

> THE UNCOMPRESSED DENSITIES OF TERRESTRIAL PLANETS <u>DECREASE</u> (SLIGHTLY) WITH INCREASING SOLAR DISTANCE.

The above statement is most accurate only if the Earth-Moon system is lumped together.

Table 6

PLANETARY DENSITIES AND COMPOSITIONS

Planet	Mass Earth = 1	Radius Earth = 1	Mean Density	Uncompressed Density	Percent Iron-Nickel Phase
Mercury	0.0543	0.38	5.46	5.4	72
		0.403	4.58	4.5	50
Venus	0.8136	0.961	5.06	4.4(?)	45
Earth	1	1	5.515	4.4	45
Moon	0.012304	0.2728	3.34	3.31	0
Mars	0.1080	0.520	4.24	4.02	30
		0.523	4.17	3.95	27

2.4.4 Lack of Heavy Volatiles on Earth

Almost all theories for the origin of the solar system start with a "cosmic" (i.e., nearly solar) abundance of raw material. It should be pointed out that solar abundances have recently been questioned - past observations may only reflect the chromospheric abundances. It is relevant to look at present-day abundances on Earth and see which elements are clearly deficient or abundant. Light, gaseous elements such as hydrogen and helium are clearly deficient, but this deficiency is easily accounted for by escape from the atmosphere (see Section 2.4.2).

Another deficiency, as pointed out by Aston (see Urey 1957) is that the abundances of all the inert gases are substantially lower on Earth than on the Sun (Russell and Menzel 1933 confirmed that other stars have large abundances of neon). The inert gases exist in the gaseous phase at extremely low temperatures, and are very volatile. If one makes the assumption that the primordial matter which ultimately went into making up the solar system was at or near cosmic abundance, then some mechanism must be found for getting rid of neon, argon, xenon, krypton, etc. Thus there is a boundary condition on theories of the origin and evolution of the solar system:

> THE EARTH, AND PROBABLY OTHER TERRESTRIAL PLANETS, HAVE MUCH SMALLER THAN COSMIC ABUNDANCE OF HIGHLY VOLATILE ELEMENTS, INCLUDING THOSE OF HIGH MOLECULAR WEIGHT.

It was shown in Section 2.4.2 that planets as massive as the Earth, even with high exospheric temperatures, will retain neon and all heavier rare gases over a five billion year time scale. Therefore, evaporation, even with an exospheric temperature elevated far above Earth's present exospheric temperature, is insufficient to account for the lack of these heavy gases. Therefore, the boundary condition above is very important in that substances which are gaseous at low temperatures were probably lost from the solar system by non-evaporative processes such as momentum transfer from the solar wind.

2.4.5 Normal Abundance of Medium-Volatile Elements

Ter Haar (1948), followed by Urey (1951, 1952), suggested that solid bodies formed or accumulated in the solar system at low temperatures. His evidence is as follows: Under reasonable conditions of pressure, and assuming cosmic abundance, which implies a reducing environment, the elements carbon and oxygen would be locked up in molecules which are gaseous at temperatures above about 400°K (carbon in CH_4, C_2H_2, CO, CO_2, and oxygen in H_2O, CO, and CO_2).

Urey (1954) has extended the arguments to other elements in both a reducing and a non-reducing environment. He concludes that there are very large differences in volatilites of the elements mercury, cadmium, zinc, silicon, magnesium, calcium, and aluminum. Mercury is 12 orders of magnitude more volatile than aluminum or calcium at 1500°K in a reducing atmosphere. Yet these elements show no significant departures from cosmic abundance, leading to the boundary condition on theories of the origin and evolution of the solar system:

> RELATIVE ABUNDANCES OF ELEMENTS WHICH DIFFER IN VOLATILITY BY ORDERS OF MAGNITUDE AT ELEVATED TEMPERATURES, BUT NOT AT ~ 300°K, DO NOT DEPART SIGNIFICANTLY FROM COSMIC ABUNDANCE.

2.5 Boundary Conditions Imposed by Isotopic Ratios

2.5.1 Light Element Isotopic Ratios

The importance of both the existence and the observed isotopic ratios of some light elements have been emphasized in a thorough paper by Fowler, Greenstein and Hoyle (1962). They show that production of deuterium, lithium, beryllium, and boron is difficult by "ordinary" nuclear processes. Furthermore,present knowledge of their isotopic ratios is independent of low energy processes, i.e., chemistry. Therefore, the isotopic ratios were probably the same just after planets were formed as they are now.

The ratios of the abundance of isotopes $D^2:H^1$, $Li^6:Li^7$ and $B^{10}:B^{11}$ each show little variation from all terrestrial (and meteoritic) samples. Leighton (1958) tabulates these isotopic ratios, which form the boundary condition:

> THE RATIO OF DEUTERIUM TO HYDROGEN IS 1.5×10^{-4}, THE RATIO OF Li^6 TO Li^7 IS .08; THE RATIO OF B^{10} TO B^{11} IS .23.

We must now inquire as to likely isotopic ratios of primordial hydrogen, lithium and boron. Fowler, Burbidge and Burbidge (1955) conclude that deuterium, lithium, beryllium and boron are not generated through reactions in stellar interiors, and it is quite clear that temperatures which must exist in stellar interiors will rapidly (10,000,000 years) deplete any existing D, Li, Be, B. Lithium has been detected on a few stars, but average stellar abundance is much lower than terrestrial. Deuterium has not been detected in the stellar atmosphere, and the upper limit to its abundance, relative to H^1, is an order of magnitude less than the $D^2:H^1$ isotopic ratio found in terrestrial oceans (Kinman 1956).

There is general agreement that these isotopes arise in nuclear reactions of a non-thermal nature somewhere outside stellar interiors. One method for production of otherwise forbidden light elements is bombardment of solid surfaces by stellar protons. Such "spallation" can produce D, Li, Be, B, but with $Li^6:Li^7$ and $B^{10}:B^{11}$ ratios of the order of unity. If the above process is important, then the boundary condition imposed by the isotopic ratios should be altered to include the change of the amounts of lithium 6 and boron 10 relative to lithium 7 and boron 11 from approximately unity to the observed isotopic ratios.

2.5.2 Meteoritic-Terrestrial Xenon and Silver Isotopic Ratios

Cameron (1962, 1963) has used experimental determination of isotopic ratios of the elements of xenon and silver in meteorites, relative to the isotopic ratios on Earth, in order to date certain processes occurring in the early history of the solar system.

From the work of Reynolds (1960a, b, c) and others it is now known that the isotopes of xenon having mass numbers 129, 131, 132, 134 and 136 are much more abundant relative to Xe^{128} in stone meteorites than they are on Earth, and somewhat more abundant in iron meteorites than on Earth. The total amount of xenon is a considerably larger fraction of the total mass of a meteorite than it is of the Earth, and the meteorites used for the detailed studies are those which contain the largest fraction of xenon, the carbonaceous chondrites. Among these meteorites, the xenon isotopic ratios show very small scatter from meteorite to meteorite (with some exceptions) and differ by a large amount (10-20 percent) from the isotopic ratios of xenon in the Earth's atmosphere. The overabundant nuclides turn out to be those which can arise from β-decay of fission products of low-lifetime, heavy nuclides.

The same kinds of facts turn out to be true for iron meteorites, and additionally there is a 2 percent overabundance of Ag^{107} compared to Ag^{109} (Murthy 1960). Again, Ag^{107} is a decay product of a fission product. These isotopic ratios provide a boundary condition on theories of the evolution of the solar system:

> ISOTOPES OF XENON AND SILVER WHICH ARE β-DECAY PRODUCTS OF RADIOACTIVE NUCLIDES ARE <u>OVERABUNDANT</u> IN METEORITES.

2.6 Restatement of the Boundary Conditions

In summary, the boundary conditions on theories of the origin and evolution of the solar system that were discussed in this section are:

1. The angular momentum per unit mass of the Sun is less than that of the planets by a factor of more than 10,000.
2. The Sun's rotation speed is not unusual when compared to other stars of the same spectral class.
3. The Sun was probably very large and bright for $\sim 10^6$ years; it was then very active during some or all of the next $\sim 10^7$ years; its surface temperature probably never exceeded ~ 6000°K.
4. The inclinations and eccentricities of the planets and asteroids are very low; their orbital radii follow an empirical law (Bode's law) approximately.
5. Regular satellites have extremely low inclinations and eccentricities; their orbital radii follow a "Bode's law" less well than do the planets.
6. The planets and asteroids rotate with small variations in period, except for Venus, Mercury and Pluto; they tend to have fairly low obliquity.

7. The density histogram of Figure 10.

8. Based on gross physical properties, planets fall into two classes, Jovian (large, low density, low molecular weight) and terrestrial (small, high density, high molecular weight).

9. The uncompressed densities of terrestrial planets decrease (slightly) with increasing solar distance.

10. The Earth, and probably other terrestrial planets, have much smaller than cosmic abundance of highly volatile elements, including those of high molecular weight.

11. Relative abundances of elements which differ in volatility by orders of magnitudes at elevated temperatures, but not at $\sim 300°K$, do not depart significantly from cosmic abundance.

12. The ratio of deuterium to hydrogen is 1.5×10^{-4}, the ratio of Li^6 to Li^7 is .080; the ratio of B^{10} to B^{11} is .232.

13. Isotopes of xenon and silver which are β-decay products of radioactive nuclides are overabundant in meteorites.

3. THEORIES OF THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

This section consists of a brief discussion of some of the more prominent theories which are presently thought to contribute significantly to man's understanding of the origin and evolution of the solar system.

A large number of theories have been proposed, and all make some contributions to our understanding. Because of their great number and complexity, we consider here only a representative sampling (with apologies to those theorists who have made substantial contributions which do not appear here due to time and space limitations).

Criteria chosen for theory selection are:

(1) The theory must be in at least general accordance with presently known boundary conditions.

(2) The theory must be "popular," i.e., widely referred to in the current literature.

3.1 Classes of Theory

Theories of the origin of the solar system can be divided into three classes. The first class is called "catastrophic". In all catastrophic theories, the Sun is considered to have formed without planets. Later it undergoes a close encounter or collision with one or more stars. Hot gasses are torn from the Sun to be used ultimately for planetary formation.

The major motivation for generating catastrophic theories was the difficulty early theorists had in accounting for the uneven distribution of angular momentum within the solar system by less violent processes. Catastrophic theories (see for example, Jeans 1929 and Lyttleton 1936, who also discuss and reference earlier work) overcome the angular momentum problem because the passing star(s) could readily exchange angular momentum with the material pulled from the Sun and even with the Sun itself in an arbitrary fashion, dependent on details of the encounter.

There are three strong objections to such theories. A fundamental objection to a catastrophic theory is the result of calculations by Nölke (1930) and by Spitzer (1939), who showed that material pulled off of our Sun is so hot that it would rapidly dissipate into space because of tidal and pressure forces. It would thus not be retained by the Sun long enough to form planets.

Also, the probability of a sufficiently close encounter by our Sun with another star is very small. One finds that, on the average, a given star will encounter another star closely enough to pull off material only if the star density is many orders of magnitude greater than at present. It has been argued that star density was much greater in the past than now; thus increasing the collision probability. Recent observations, however, indicate an age of the universe and of the galaxy considerably larger than the age of our Sun. Therefore the probability that the stars were significantly denser at or after the Sun's birth is not very high.

Finally, the results of Section 2.2, which indicate small rotation speeds for stars like our Sun, imply that all such stars have low angular momentum. Therefore, the movitation for catastrophic theories has been removed, and they have lost favor among cosmogonists. They are discussed no further this report.

A new class of theory also involves a solar collision, but rather with an interstellar cloud of gas and dust, a much more probable process than a Sun-star encounter. Schmidt (1944) outlined the theory, and Russian astronomers especially have found it attractive. This theory does not contain the objections that made catastrophic theories unpopular. In the first place, the probability of the Sun's encounter with such a cloud is much higher than a stellar collision, although it is still rather improbable. Secondly, the gas and dust in the cloud is assumed to be cold, and there is probably sufficient time for planetary formation to occur making use of the captured material. Again, there is no angular momentum problem because the cloud can have almost any initial angular momentum with respect to the Sun, thus making the Sun's angular momentum independent of that of the planets.

The final class of theory starts with a single cloud of interstellar material out of which the Sun, the planets, and the smaller bodies of the solar system evolve. The cloud at some time exceeds a critical density and size and contracts, such that the center portions of the cloud form the Sun, and the outermost portions escape or form planets. Most non-Russian cosmogonists now subscribe to this "evolutionary" theory.

Conditions under which cloud contraction can begin, and how viscous and hydromagnetic effects can inhibit solar rotation are discussed in some detail in the appendix.

3.2 Individual Theories for the Origin and Evolution of the Solar System

3.2.1 Theory of Kant and Laplace (1755, 1796)

Kant (1755) and Laplace (1796) (see discussion by Berlage 1948) were the first to propose the hypothesis that the solar system was formed out of scattered matter. The authors regarded the process as a regular development of matter that followed the laws of nature, and inferred that great changes have taken place since the beginning of the solar system.

Both Kant and Laplace built up their hypotheses on the idea that the Sun and the planets were formed out of dispersed matter, and their ideas were so similar that they have become merged into one theory. Laplace said that the primordial nebular medium was gaseous, while Kant used the term "particles," which may be understood as gas, dust or any other small bodies. The difference can be significant, since the presence of dust or other small solid particles in a solar nebula facilitates the redistribution of energy and the transformation of part of the kinetic energy into heat. Secondly, Kant speaks of the gradual accretion of particles that collide during motion as a condition for their growth, while Laplace's planets are formed from the condensation of gas. Both of these thoughts were later developed further. Kant's hypothesis did not include the separation of rings from the contracting Sun (due to rotational instability) that played such an important part in Laplace's theory and was of more interest to his followers than anything else.

The joint hypothesis could not, however, cope with the angular momentum problem. Kant erroneously imagined that angular momentum was generated in the process of evolution, while Laplace, by assuming it to be present from the very beginning (the rotating nebula), could not explain the anomalous distribution of the angular momentum between the Sun and the planets and ignored it.

Their concepts were, of course, limited by the level of 18th century scientific knowledge. Not only were immeasurably fewer facts known, but such things as the law of conservation of energy and the transformation of one form of energy into another had not yet been established. There further was no science of thermodynamics or statistical mechanics in existence. Though their theory had many shortcomings, Kant and Laplace did make a break in metaphysics; their hypotheses were built upon the regularities in the structure of the solar system as they were known at that time and provided an explanation for a number of facts.

3.2.2 Alfven (1942-1954)

Alfven's theory (1942, 1954) considers the solar system development from the time at which a rotating magnetic (surface field ~ 1 gauss) Sun had formed and was surrounded by a solar "nebula". The nebula at that time had a solar mass and was within 0.1 light years from the Sun, half of it being within 50 AU. As the material in the nebula fell in toward the Sun, collisions caused ionization, so that subsequently motions were governed almost solely by the Sun's magnetic field. Alfven calculated the force on a proton in the Earth's orbit due to the Sun's magnetic field to have been greater than its gravitational force by a factor of 60,000.

The Sun's field served to separate different elements on the basis of ionization potential. An element relatively difficult to ionize, like helium, fell relatively close to the Sun before solar radiation was strong enough for ionization. Alfven speaks of four main clouds, each requiring different ranges of temperature to ionize different elements. Each group, of course, had "impurity" elements from all the other groups. The A cloud was composed of high-ionization-potential material and fell very close to the Sun. The B-cloud was stopped in the region of terrestrial planets; the C-cloud near Jupiter, Saturn, and Neptune, and the D-cloud beyond Neptune. The procedure is shown to explain, in part, the difference in the gross physical properties of the Jovian and terrestrial planets.

Alfven also explains the angular momentum distribution. As soon as a particular cloud is ionized, electromagnetic forces tend to accelerate the cloud material to the same angular velocity as that of the central Sun. The fields are coupled from Sun to clouds by a tenuous plasma. Angular momentum transfer is accomplished in only a "few years" and, as the material begins to spin rapidly, the increasing centrifugal force which is produced brakes its inward motion, resulting in accumulation at certain distances from the Sun.

Condensation enabled the gas which was at this point less ionized to form drops or grains on solid nuclei present in the original nebula. Electrostatic effects aided the condensation. The grains and drops accreted into larger and larger bodies, ultimately forming planets and satellites.

Later theorists have rejected many features of Alfven's theory, especially the separation of elements on the basis of ionization potentials, because the temperatures required for even modest ionization are thought to be much higher than actually existed in the nebula. Alfven's novel injection of hydromagnetic forces to solve the angular momentum problem has endured, and has greatly influenced later work.

3.2.3 Schmidt (1944-present)

Prior to the 1940s, the two possibilities concerning the origin of the solar system were (1) Sun-star interaction (collision), with material being torn out to form planets, and (2) "simultaneous" formation of Sun and planets from a single interstellar cloud. O. Y. Schmidt (1944) rejected both of these and assumed that a cloud of gas and dust was captured by the pre-existing Sun as it traveled through a rarefied nebula. According to this capture hypothesis, part of the matter of the nebula was carried away with the Sun and continued to move together with it and revolve around it.

The dust particles of the cloud become separated from the gas by solar radiation. They tended to collect towards the equatorial plane of the cloud, which was flattened because of the rotation. The mutual gravitational attractions between the particles gradually increased because of the smaller separation. The result was the agglomeration of matter into bodies intermediate in size between the primordial particles and the present planets. Some of the larger bodies finally became the planets by gradual accretion of the smaller bodies and fragments. The frontispiece shows Schmidt's evolutionary sequence of planetary formation from the nebula stage to the present configuration.

Schmidt's followers (Gurevich 1950, Lebedinsky 1953, Levin 1962, et al.) employed kinetic theory to show that a system of solid particles with great angular momentum and sufficient total mass could follow the evolutionary sequence proposed by Schmidt. Their work shows that, prior to the fission of many particles, the small bodies moved along extreme elliptical orbits; when a number of bodies became fused, the velocities were averaged and the large planet, formed as a result, moved along an almost circular orbit. The minor planets and small bodies which exist today continue to move along the original elliptical orbits.

In the period of formation each new planet was surrounded by a collection of small bodies; the majority fell on the planets' surface but some fused into satellites which continue to orbit the particular planet.

This theory also suggests that the inner planets were formed from small solid particles heated by the Sun's rays; the composition of these planets includes almost no highly volatile gases. On the contrary, cosmic dust which formed the outer planets had a very low temperature, being much further from the Sun, so that volatile gases froze to it. As a result, masses of the outer planets turned out to be very large, while their density, due to the abundance of hydrogen, is much smaller than that of the inner planets.

Besides introducing the new class of solar system origin theory based on cloud capture, the theory of Schmidt and followers has made several contributions which are relevant to all theories. The importance of solids in planetary formation has generally been favored by later theorists. The detailed study of the accretion mechanism has corrected a number of previous misconceptions, and can even be used to account for the present direction of rotation of most of the planets.

3.2.4 Von Weizsäcker (1944-1946)

Von Weizsäcker (1944, 1946) (also see Chandrasekhar 1946) assumed planets were formed out of a regular pattern of turbulent eddies revolving around a central star, the Sun. The starting point is a flattened solar nebula, of mass 0.1 $M_{\odot}$. Because the Reynolds number is so large ($\sim 10^{21}$) the fluid motion was highly turbulent (see appendix). The turbulent velocities were assumed to have been about 20 km/sec, which is comparable to the relative velocities of neighboring stars. The eddies ranged in size from a collision mean free path to nearly the size of the nebula. An entire spectrum of eddies is built up on the basis of their size and velocity.

The solar nebula is assumed to have formed with a rather high density ($10^{14}/cm^3$), having a mean free path of the order of 1 cm. Each part of the nebula revolved around the Sun in a free Kepler orbit and, as turbulence developed, a turbulent pattern was superimposed on the Kepler rotation. Von Weizsäcker, searching for a pattern which would cause the least dissipation of energy by viscosity, chose a complicated set of epicycle eddies. Condensation is assumed to have started where eddies touched each other. Subsequent building up of larger solid bodies is expected to have proceeded rapidly. Finally, when a certain critical radius was passed, gravitational effects become dominant and increase the rate of growth of the body by gravitational instabilities. The rate of growth of the planetesimals in the initial stages was assumed to have been proportional to time. There is some uncertainty in the overall time scale, though, since the relative velocity of impacting particles is some sort of weighted mean of the relative particle velocity and the thermal velocity. If the temperature of the gas was roughly 300°K/$\sqrt{a}$ (where a is the distance to the Sun in astronomical units), then a small condensation would form in $\sim$30 years and a body some 2000 km in diameter would be formed in some 3 x 10^7 years. Since the lifetime of the solar nebula was computed to be 10^7 years, condensation stopped with the formation of 1000 km planetesimals. Final planetary formation is envisioned to have proceeded by accretion. The particular original eddy pattern originally assumed led to the Jovian planets arranged according to Bode's law.

Von Weizsäcker's theory made a substantial contribution to understanding the origin of the solar system by introducing turbulent viscosity to solve the angular momentum problem. Unfortunately, turbulence was not well understood when he began his work, and some of his quantitative calculations of eddy decay rates and velocity spectra are incorrect. Kuiper followed Von Weizsäcker with a theory retaining a turbulent solar nebula, but incorporating later work on the structure of turbulence.

3.2.5 Kuiper (1949-1954)

Kuiper's work (summarized in Kuiper 1951) extended Weizsäcker's theory and added a large amount of astronomical and other evidence as boundary conditions.

Kuiper used Kolmogorov's spectral law of turbulence (unknown to Von Weizsäcker), to show that Von Weizsäcker's pattern of vortices was very unlikely to form, and once formed could not last for a time required for planetesimal formation. In particular, vortices would be unequal in size; the larger ones would arise further away from the Sun.

In determining a plausible density distribution in the solar nebula, Kuiper included the effects of solar tidal forces. He showed that a condensation would be unstable if the net difference in the Sun's attractive force on any two neighboring elements exceeds the mutual gravitational attraction between them. In that case the tidal forces of the Sun will overcome the self-attraction of the elements, and a condensation cannot occur. The critical density below which condensation cannot occur is given by $6M/\pi R^3$, the local Roche limit, where M is the solar mass and R is the distance from the Sun.

Based on condensation at the Roche limit, all primordial condensations are shown to have had about the same mass, which was somewhat larger than Jupiter's present mass. This raised a difficulty in the light of the present disparity in planetary masses. However, Kuiper attributed these mass differences to subsequent evolution of the Protoplanets," i.e., large bodies which shrink to form planets. The terrestrial planets lost mass because they were close to solar radiation. Uranus and Neptune became smaller because lost material could not be recaptured since it would leave the solar system.

Further, during the course of the protoplanets' contraction, they were all strongly affected by solar tides, which imposed a synchronous rotation. This is a consequence of the fact that condensations occur at the Roche limit, so that solar tidal forces and internal attraction were balanced for each protoplanet at the start of condensation. As these protoplanets contracted, however, the density increased and the tidal forces became less effective. With the attenuation of the braking effect of solar tides, the rotation of the planets increased due to conservation of angular momentum. The planets thus began to rotate with periods smaller than their orbital periods, the rotation being direct for all cases.

A very attractive feature of Kuiper's work is that much of the astronomical evidence cited in Section 2.2 is accounted for. Planetary formation is considered as a special case of a universal process which also leads to binary-star formation. If the mass of the nebula happens to be large, a single condensation is formed, thus leading to a binary star system. If it is small, a solar system full of asteroids, but no planets, is formed. Only in the intermediate case is a system with a few planets the end result.

Kuiper differs from most other theorists in that he suggests condensation leads to protoplanets and with subsequent evaporation leading to planets, rather than condensation to form planetesimals and subsequent accretion to form planets.

3.2.6 Fowler, Greenstein, Hoyle

The cosmogony of Hoyle, Fowler, Greenstein and others is set forth in a number of papers, the most important of which are those of Hoyle (1960) and Fowler, Greenstein and Hoyle (1962). The starting point is a low-density interstellar cloud which contracts to form a central Sun and an equatorial disk of solar nebula of low mass (10^{-2} $M_{\odot}$). At this point, the Sun was large (radius of 40 R_J), cold (~50°K), and spinning rapidly.

Hoyle showed that the Sun's spin could have been slowed by hydromagnetic forces even in a cold, weakly ionized nebula, which acquires angular momentum and recedes from the Sun so that the solar system is like a T-Taurid, with mass flow out. Solid particles condense, and these condensations grow. If they grow enough, the drag on them by the outflowing gas is insufficient to entrain them and they are left behind as planetesimals.

Fowler, Greenstein and Hoyle have been able to use the boundary condition of light element isotopic ratios to determine the size of the planetesimals. The Sun is assumed very active and irradiates the condensations with energetic protons, some of which, upon nuclear reactions, generate neutrons. The energetic protons create elements not originally present in the nebula, such as lithium, beryllium, and boron (Li, Be, B), with isotope ratios $Li^7:Li^6$ and $B^{10}:B^{11} \sim 1$. Neutrons, having been thermalized by scattering in the planetesimals, deplete

Li^6 and B^{10} (and increase Li^7 slightly) by the following high-cross-section reactions:

$$Li^6 + n \rightarrow H^3 + \alpha$$

$$B^{10} + n \rightarrow Li^7 + \alpha.$$

The planetesimals during this stage must have dimensions of the order of magnitude 1-50 meters. If smaller, not enough shielding would be present to prevent removal of isotopes like Gd^{157}, which have high thermal neutron cross-sections but which are observed with normal isotopic abundance. Also, if smaller, the planetesimals could not separate from the outflowing gas of volatiles. On the other hand, if they are too large (>50 meters), the neutron reactions are too inefficient to produce the observed Li^6/Li^7 and B^{10}/B^{11} isotope ratios.

Near Jupiter and Saturn, the mass flux outward was reduced, and hydrogen and helium was present during condensation. This prevents the above nuclear processes from occurring. Subsequently, Jupiter and Saturn were formed with hydrogen and helium. Near Uranus and Neptune the flow was absent, but the solar gravitational field was too weak to prevent evaporation and solar system escape of volatiles, leaving less H, He on these planets.

The theory stops here, leaving planet formation to accretion by planetesimals.

3.2.7 McCrea (1957-present)

In the theory of McCrea (1957, 1960) the origin of the solar system is also related to the general problem of star formation.

The Sun was formed at a time when the galaxy was essentially as it is now, and was probably a member of a cluster. McCrea states that, because of angular momentum problems, a star cannot be formed by the condensation of all the material originally within any one particular region of the interstellar medium, but rather by the accumulation of parts of material from various regions. It is to be supposed that the original material is in a state of chaotic motion and that a portion of material goes into a particular condensation (which is going to form a star) simply because it happens to be moving toward that particular condensation slowly. This automatically guarantees that material going into a star does not impart much angular momentum to it. Further it suggests that the solar system origin was concerned with a much larger system than a "solar nebula".

"Floccules" are the basic building blocks of the theory. These are clumps of gas and dust wandering through space. Collisions can produce larger (and more substantial) floccules. Eventually, condensations become of sufficient size to contract under self-gravitation (see appendix), which eventually grow into stars. Mutual encounters between floccules or minor condensations in the gravitational field of a large condensation (star) will result in some material being captured into closed orbits around the star (planetary systems).

Initial conditions are assumed to have been:

Mean density of "cloud" = 4×10^{-2} g/cm^3

Number of floccules within the contracting cloud = 10^5

Mean free path of floccules = 5×10^{11} cm

Random speed of floccules = 10^5 cm/sec

Average temperature = 50°K.

Under these postulates, nearly all of the mass ultimately goes into forming the Sun. Because the floccules arrive at the embryo Sun from random directions, the most probable value of the resultant angular momentum is about $\sqrt{N}J$, where N is the number of floccules, and J is the angular momentum of a single floccule. For the assumed conditions, this is the same order of magnitude as the actual angular momentum of the Sun. (It is estimated that the Sun acquired 90 percent of its mass in about 7×10^4 years, with another 10^5 years needed for the additional 10 percent.)

The floccules which remain after the Sun has formed have (on average) high angular momentum, and form a flattened solar nebula, taking about 10^4 years. During the flattening, two related processes are important. The collisions between floccules that produce the flattening will result in some of the material losing angular momentum and falling into the Sun.

Also, condensations will form. This is a repetition of the sort of process that led to the formation of the Sun, but it now takes place in material trapped locally in the Sun's gravitational field.

McCrea, like Kuiper, considers tides produced by the Sun. He shows that a floccule is stable against breakup only at the distance of Jupiter and beyond. McCrea therefore considers his theory valid only for the major planets. The formation of the inner planets is left to depend upon some other criterion. It is suggested that the asteroids resulted from a condensation at just about the Roche limit.

The theory is shown to satisfy a large number of the boundary conditions set forth in Section 2 from a remarkably small number of postulates, and, for this reason, is attractive, even though the heart of the theory, namely the separate existence of individual floccules, may not be too realistic.

3.2.8 Cameron (1962-present)

Cameron (1962, 1963) has given a theory which interprets the boundary conditions imposed by xenon and silver isotopic ratios found in meteoritic and terrestrial samples. His major contribution is in dating events early in the solar system's history.

Cameron assumes that, as the material forming solar system contracts, it becomes isolated from the injection of any further radionuclides in the interstellar medium, so that the existing level of radioactivity decays.

Decay products of radioactive nuclides become enriched, and the parent nuelci become depleted. For β-decay processes, parent and daughter are different elements, and fractionate chemically. From the isotopic ratios of the daughter (xenon and silver), and the chemical abundances of parent and daughter, Cameron has estimated the time between isolation of the solar system from the interstellar medium and the cessation of fractionation of parent and daughter elements. Figure 11 shows Cameron's results.

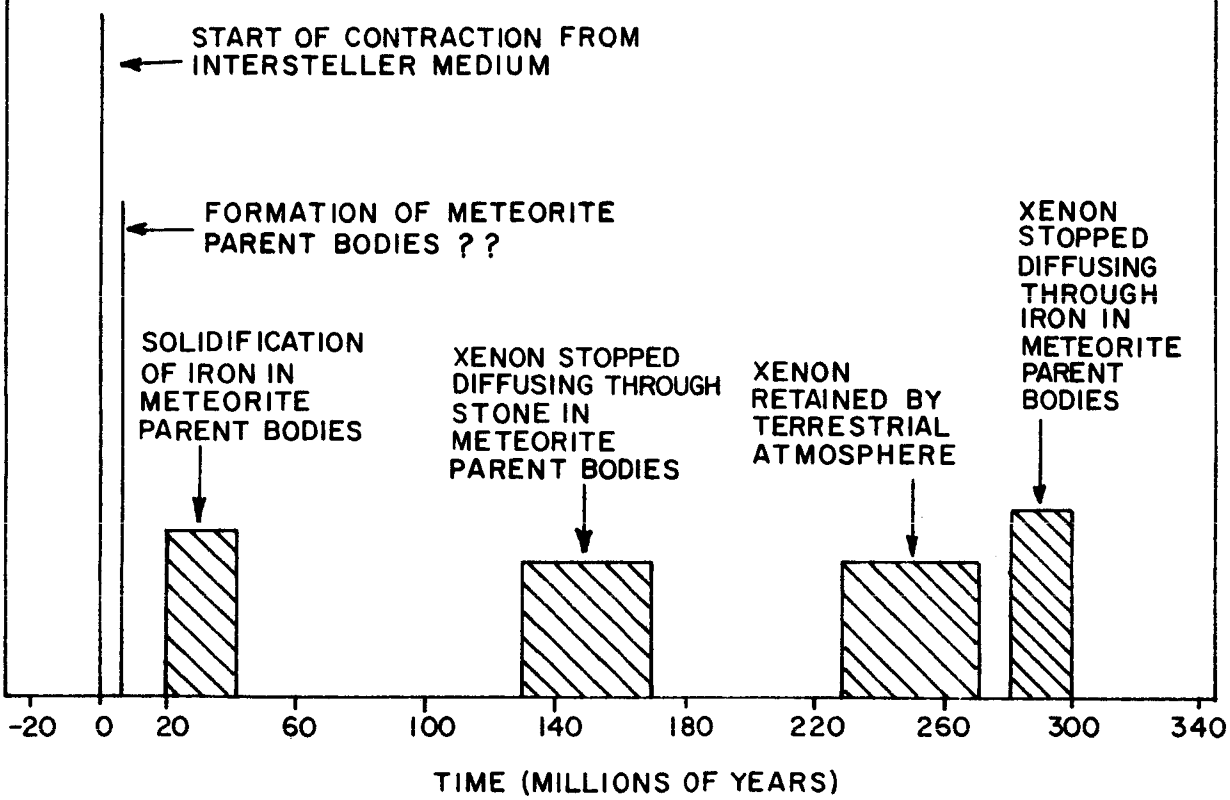
The first interval, from isolation to the formation of meteorite parent bodies, is not based on evidence of isotopic ratio. Based on the assumption of a minimum amount of the extinct radionuclide Al^{26}, the time from the start of contraction to the thermal insulation of meteorite parent bodies is less than $\sim 10^{6}$ years.

The second interval (20-40 million years) is the time taken for meteorite parent bodies to reach the melting temperature of iron. This is based on the silver isotopic ratios cited earlier, and is the point at which the daughter, Ag^{107} is not fractionated from the parent, Pd^{107}.

The next interval (130-170 million years) is the time taken for xenon to stop diffusing through stone meteorites, which should occur at about 200°K. This is based on the xenon isotope ratios in stone meteorites, and is the point at which the daughter isotopes of xenon are not fractionated from their parents.

FIGURE 11

EARLY CHRONOLOGY OF SOLAR SYSTEM



The time interval associated with the retention of Xe in the Earth's atmosphere seems to be about 2.5 x 10^8 years, but this number is difficult to estimate, and is subject to wide uncertainty.

Finally, the small overabundance of decay isotopes of Xe in iron meteorites enables Cameron to date the cessation of fractionation (cessation of xenon diffusion through iron meteorites) as 280-300 million years after meteorite parent formation.

3.2.9 Urey (1951-present)

Urey's work (e.g. Urey 1963), like Cameron's, is concerned primarily with early solar system history. More than anyone else, he has given and interpreted the boundary conditions imposed by chemical evidence (see Section 2.4.3, 2.4.4, 2.4.5) and devised a theory which accounts for them.

Urey proposes that the Sun and a flattened nebula of gas and dust were originally formed out of a solar cloud at $\sim 0°C$. In the region of the terrestrial planets, at least, volatile elements (H_2, He, Ne, A, Kr, etc.) were swept out. The chemical composition includes silicates, FeO, FeS, some metallic iron, ice, NH_3 and carbon compounds. Planetesimals formed out of the disk material at low temperatures consisted originally of silicates, FeO, FeS, hydrated minerals, NH_4Cl, solid H_2O, NH_3, and carbon compounds, and locked-in elements of medium volatility. A high temperature ($\sim 2000°K$) stage occurred next, resulting in reduction of iron oxides, loss of gases and volatilization of silicates or solid silicate particles. The large planetesimals then consisted of FeO, hydrated minerals, FeS, NH_4Cl, metallic iron, C, Fe_3C, TiN and carbon compounds, while the smaller ones contained silicates and iron compounds. This was followed by a second low temperature stage, marking accretion to planets.

Urey emphasizes the importance of solid bodies and the physical and chemical processes to which they were subjected. The absence of any observable fractionation of elements less volatile than mercury and its compounds (in the case of the meteorites and of the Earth), indicates generally low temperature accumulation and subsequent heating only under conditions leading to very limited loss of elements which are volatile only above 1500°K.

3.3 Summary of Conclusions of Prominent Theories

Although there are substantial differences among the various theories described, there are also several points where the theories converge to one or two particular solar system configurations. Therefore, it is possible to discuss the theories as a whole, and to show where they converge and where they diverge.

Table 7 and the frontispiece summarize the conclusions of the theorists of Section 3.2 at various stages in the origin of the solar system. The solar nebula is formed either by contraction of a single cloud or by the capture of a cloud of interstellar matter by an already existing sun. In either

Table 7

SOME CONCLUSIONS OF PROMINENT THEORIES

Important Features / Theorist(s)	Kant-Laplace	Alfven	Schmidt	Von Weizsäcker	Kuiper	Fowler, Greenstein-Hoyle	McCrea	Urey	Cameron
Mode of solar system formation*	S.C.	S.C.	Capture	S.C.	S.C.	S.C.	S.C.	(S.C.)	(S.C.)
Mass of nebula**	+	1 $M_\odot$	Low	.1 $M_\odot$	.1 $M_\odot$	.01 $M_\odot$	+	.3 $M_\odot$	.1-.3$M_\odot$
Original temperature	?	>1000°K	<100°K	~300°K	~300°K	~100°K	<100°K	<100°K	<100°K
Solution to angular momentum problem	Unsolved	MHD++	Not relevant	Turbulent viscosity	Turbulent viscosity	MHD	Statistical	(MHD)	(MHD)
Solids formed by condensation?	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Accretion of solids important?	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Evaporation necessary?	?	No	No	?	Yes	No	No	No	No

* S.C. denotes formation of system from interstellar or (solar) cloud.

** At start of angular momentum transfer and/or condensation processes.

\+ Continuous nebula not used in these theories (Kant-Laplace employ a system of rings; McCrea makes use of "floccules").

() Parentheses indicate that the theorists accepts the mode within the parenthesis, but does not contribute to its development nor is it necessary for his later conclusions.

? A question mark indicates that it is not clear what conclusions are reached or assumed.

++ Magnetohydrodynamics.

case a flattened nebula is formed around a sun which in most theories is spinning rapidly. Conditions of temperature and total mass in the nebula vary greatly from theorist to theorist, as can be seen from the table. If the sun is spinning rapidly when the nebula has formed (only Schmidt and McCrea arrive at a slowly spinning sun at this stage), the modern theorists envision a transfer of angular momentum from the sun to the nebula via hydromagnetic (MHD) or viscous forces. Planetary formation now proceeds. Except in Schmidt's theory, which has relatively large solid objects in the nebula from the start, solids condense out of the gasses in the nebula. Two theorists, Kuiper and probably McCrea, envision a few very large condensations, which proceed to planetary size (McCrea) or even larger (Kuiper's protoplanets). The other theorists envision a large number of smaller condensations which form solid planetesimals, whose size varies among theorists (e.g., Urey's planetesimals are moon-sized; Fowler, Greenstein and Hoyle's are boulder-sized). Finally, Kuiper's protoplanets lose mass by atmospheric escape, while the planetesimals of other theorists are fused together to form planets by accretion.

Although most of the theories described reach certain conclusions at various stages in the solar system origin and evolution, the emphasis on the various stages differs considerably from theory to theory. Table 8 shows the significant

Table 8

CRITIQUE OF PROMINENT THEORIES

Theorist(s)	Significant Features	Most Apparent Weakness(es)
Kant-Laplace	One of the first to propose formation of the entire solar system out of the same material.	Fails to explain angular momentum disparity.
Alfven	Solar magnetic field interacted with ionized cloud (MHD forces) to form planets differentiated chemically on the basis of ionization potential.	A large number of probably unrealistic requirements and assumptions are necessary for the full theory, especially the ionization process and sudden changes in molecular collision times.
Schmidt	Solar system originated with cloud capture by a pre-existing Sun. Solids in a cold cloud are of primary importance.	Improbability of a Sun capturing part of an interstellar cloud, because of the low relative velocities required.
Von Weizsäcker	Turbulent properties of the interstellar cloud were predominant in establishing planets; a regular system of vortices can lead to Bode's law for the Jovian planets.	Later work on turbulence shows that the system of vortices assumed is difficult to establish and probably impossible to maintain for the time required for planet formation.
Kuiper	Extension of Von Weizsäcker's work uses a much more reasonable consideration of eddy and vortex development. A very complete theory using astronomical evidence and leading to protoplanets.	Very difficult to account for lack of heavy volatiles on terrestrial planets; some possible confusion between thermal velocity and turbulent velocity.
Fowler-Greenstein-Hoyle	Sun and equatorial disk formed from contracting cloud magnetic coupling between Sun and weakly ionized disk. Solid objects (1-50 meters in size) exist from .4-4 AU after hydrogen has left region.	No obvious criticism at this time; theory only recently proposed.
McCrea	Original material in chaotic motion, in form of "floccules", which interact and lead to condensations and planets. Very few assumptions about floccule conditions are required to explain a large number of boundary conditions.	Stability of floccules questionable. Inner planet formation left somewhat undefined.
Cameron	Early history of solar system, especially the times taken for formation and cooling of meteorites and the Earth, is concluded from various isotopic abundances.	No obvious criticism at this time; theory only recently proposed.
Urey	Most extensive treatment of boundary conditions imposed by chemical evidence; solids important in planetary formation; and the original nebula cool.	No obvious criticism at this time; theory only recently proposed.

features of each of the theories described in this report, and summarizes the more important weaknesses which have become apparent since the theory has been given.

3.4 Whether the Theories Fit or Do Not Fit the Boundary Conditions

The aim of a theory of the origin and evolution of the solar system is, of course, to describe what actually took place. This certainly requires that the theory fit the boundary conditions, and also that it be based on sound physical principles.

Table 9 is given in order to draw the comparison of boundary condition and theory. The rows of the table are boundary conditions, shown in abbreviated form. They are numbered in accordance with the unabbreviated boundary conditions given on pages 54 and 55. The columns of the table give the theorists. If their particular theory has been shown to fit a particular boundary condition, a "yes" is entered as the appropriate "matrix element". A "no" indicates that the particular boundary condition has been violated by the theory.

In order to judge how well a theory fits the boundary conditions, it is not sufficient merely to count "yes's" and "no's", because the boundary conditions are neither equally well established nor equally important. Therefore, let us consider each theory using Table and Table 9 to judge the soundness of the physical processes invoked.

Table 9

CONSISTENCY OF PROMINENT THEORIES WITH BOUNDARY CONDITIONS

Boundary Conditions* / Theorist(s)	Kant-Laplace	Alfven	Schmidt	Von Weizsäcker	Kuiper	Fowler, Greenstein, Hoyle	McCrea	Urey	Cameron
1. Angular momentum distribution	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Sun's similarity to other stars in rotation period	-	-	-	-	Yes	-	Yes	-	-
3. Early solar conditions	-	-	-	-	-	Yes	-	-	-
4a. Low planetary eccentricities, inclinations	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b. Bode's law	-	Yes	-	Yes	Denies law	-	No	-	-
5. Low satellite eccentricities, inclinations	Yes	Yes	-	-	Yes	-	-	-	-
6a. Rotation period similarity	-	-	-	-	-	-	Yes	-	-
6b. Modest planetary obliquities	-	-	Yes	-	Yes	-	-	-	-
7. The density histogram, Figure 10	-	Yes	-	-	Yes	-	Yes	-	-
8. Differences between terrestrial-Jovian planets	-	Yes	Yes	-	Yes	-	-	Yes	-
9. Densities of terrestrial objects	-	-	-	-	-	-	-	Yes	-
10. Deficiency of heavy low-temperature volatiles	-	No	Yes	-	-	Yes	-	Yes	Yes
11. Normal abundance of high temperature volatiles	-	No	Yes	-	Yes	-	-	Yes	Yes
12. Light element isotopic ratios	-	-	-	-	No	Yes	No	-	-
13. Xenon and silver isotopic ratios	-	-	-	-	-	-	-	-	Yes

*A (yes) indicates the theory has been shown to fit the boundary condition, a (no) that the theory is contradicted by the boundary condition; the use of (-) suggests that it is not well known whether or not the theory fits the boundary condition, due usually to the limited scope of the particular theory.

Kant and Laplace did not know most of the boundary conditions in Table 9. Their theory explained those known but without modification it fails to explain the uneven angular momentum distribution and, therefore, is not satisfactory in its original form.

Alfven's theory fits a large number of dynamical boundary conditions, even Bode's law, and leads naturally to the Jovian-terrestrial classification. It requires a very hot nebula during at least the start of planetesimal formation, and it is difficult to reconcile these high temperatures with the observed absence of differentiation of substances volatile at these temperatures (Boundary Condition 11). Furthermore, the theory requires a large number of ad hoc assumptions, which has led later theorists to reject most of Alfven's theory, keeping only the hydromagnetic aspects which led to a reasonable solution of the angular momentum problem.

Schmidt's theory appears to be on solid ground as far as the boundary conditions are concerned; none are violated, and the theory is able to explain many of the dynamical boundary conditions well and completely. The basic difference between his theory and some of the other planetesimal theories lies in how the solar nebula is formed, and not on conditions in the nebula or on how planets are formed out of the nebula.

Von Weizsäcker's theory does fit a few boundary conditions and violates none; on the other hand, it is almost surely not a correct explanation of solar system origin, as Kuiper pointed out, because Von Weizsäcker's vortex structure is unstable over time scales required for planet formation and seems an improbable structure.

Kuiper's theory is quite detailed and very complete. As can be seen from Table 9, almost all of the boundary conditions known when the theory was proposed are accounted for, although Kuiper is forced to postulate some unknown processes to rid terrestrial protoplanets of heavy elements which are gaseous at low temperatures. Since his protoplanet theory was proposed, Urey's considerations of a chemical nature tend to favor planetesimals over protoplanets. Furthermore, if Fowler, Greenstein and Hoyle's interpretation that the light element isotopic ratios demand planetesimals, then Kuiper's theory contradicts Boundary Condition 12, and must be rejected. It is unwise to reject such a very complete and detailed theory which fits so many boundary conditions at this time, however, before the chemical evidence and interpretation of light element isotopic ratios are digested.

The theory of Fowler, Greenstein, and Hoyle violates no boundary condition stated, and it alone explains the light element isotopic ratios. By itself, it does not consider many boundary conditions, although it can be added to other theories quite readily. It is premature to judge whether its explanation of the light element isotopic ratios is correct; they may be able to be explained in other ways.

McCrea's theory is quite comprehensive and fits several boundary conditions. It appears to violate Bode's law, but, as we have seen, Bode's law is not a very important boundary condition. Like Kuiper's theory, no planetesimal stage is passed through, and, in its present form McCrea's theory cannot account for Fowler, Greenstein and Hoyle's explanation of the light element isotopic ratios. Furthermore, the concept of a relatively stable "floccule" is open to considerable criticism.

Urey and Cameron each concentrate on a restricted portion of the solar system origin, and include the results of other theories to complete the picture. Neither theory contradicts a boundary condition; with the additions from the theories, they fit many boundary conditions.

To sum up, the origin and evolution of the solar system is becoming better and better understood as new theoretical and observational evidence is assimilated. Even so, there are many points of controversy remaining, as well as relatively poor understanding of the details of physical processes which are indispensible in the various theories.

4. FUTURE PROGRESS IN UNDERSTANDING THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

Progress in understanding the origin and evolution of the solar system has come in the past primarily from (1) obtaining and identifying boundary conditions which must be met by theories of the origin and evolution of the solar system, and (2) proposing theories of the solar system which both fit the boundary conditions and are reasonable, i.e., do not involve either violation of physical laws nor depend on extremely unlikely processes.

We shall arbitrarily split up suggestions for future work into two categories:

(1) Progress related mostly to boundary conditions, and

(2) Progress related mostly to settling controversial points in existing theories.

There is some overlap here, where extension of a known boundary condition settles a controversial point in existing theories. These overlap areas are put in category 2.

4.1 Progress Related Mostly to Boundary Conditions

Many boundary conditions, notably nos. 10 and 11 (page 55) compare presently known relative abundances of elements, isotopes, etc. with a standard "cosmic abundance". The "cosmic abundance" is derived from observations of the Sun (mostly), other stars, the Earth's atmosphere and crust, and meteorites. What is most desirable are the relative abundances with respect to the interstellar medium five billion years ago. It is likely that the composition in the interstellar medium has changed only slightly since then, and so a very important boundary condition desired for the future is:

THE INTERSTELLAR CHEMICAL AND ISOTOPIC COMPOSITION.

- A rather sophisticated spacecraft mission to the interstellar medium is almost undoubtedly required for this purpose.

The Jovian planets, especially Jupiter, are presently thought to be extremely stable against evaporation of even hydrogen from the top of their atmospheres. It would be desirable to know whether the Jovian planets, and Jupiter in particular, have a "cosmic abundance" or a solar abundance of the light elements. Therefore, as an extension of the boundary condition on the gross physical properties of the planets, it is proposed to determine the

HELIUM-HYDROGEN RATIO ON THE JOVIAN PLANETS,
ESPECIALLY JUPITER.

- Probably the most significant advance toward this end would be a determination of the strength of a helium emission line taken by a spacecraft viewing Jupiter's dark side.

Many theorists invoke either large size, luminosity, or activity to allow their theories to bridge chasms of difficulty. Kuiper's problem with heavy volatiles and Fowler, Greenstein and Hoyle's requirements of large solar proton fluxes for spallation are examples. Boundary Condition 3 (page 54) should be refined and extended, i.e.,

THE EVOLUTION OF STARS IN THEIR PRE-MAIN-SEQUENCE
PHASE SHOULD BE BETTER KNOWN.

- This undoubtedly requires both more extensive stellar interior theory, and more and better observations of very young stars.

As we have seen, Cameron has been able to date early solar system events using the xenon and silver isotopic ratios on the Earth and meteorites. If his theoretical ideas are correct, it should be possible to date the fractionation of daughter and parent nuclides on any solar system object for which the relevant isotopic ratios are measured. Therefore, an extension of Boundary Condition 13 is useful, i.e., obtain

THE XENON (AND SILVER, IF POSSIBLE) ISOTOPIC RATIOS
ON AS MANY PLANETS, SATELLITES, ASTEROIDS, AND COMETS
AS POSSIBLE.

- Rather sophisticated measurements from a lander or atmospheric probe are probably required.

In order to refine Boundary Condition 9, it is desirable to measure

THE DENSITY OF MERCURY.

- The desired accuracy can be obtained from tracking a flyby spacecraft to Mercury, and obtaining its size optically.

Most boundary conditions related to chemical composition and structure obtain their basic data from the atmospheric constituents. These boundary conditions would be more valuable if the compositions and structures of lunar and planetary interiors were better known. A number of different model interiors have been proposed for several planets. These models can be improved considerably if (1) planetary magnetic moments, configurations, and fluctuations were known (this would yield an estimate of the conductivity of the interior), (2) internal heat sources were known and identified, and (3) if the equation of state of likely materials, e.g., iron-nickel, silicates, hydrogen, at high pressure was available. Therefore, it is useful to determine

> THE MAGNETIC FIELD PROPERTIES OF THE PLANETS; THE HEAT FLUX FROM LUNAR AND PLANETARY INTERIORS; THE EQUATION OF STATE OF IRON-NICKEL, SILICATES, HYDROGEN UNDER HIGH PRESSURE.

- The magnetic field determinations almost undoubtedly require spacecraft measurements; obtaining equations of state require Earth-based theory and experiment; obtaining heat fluxes probably requires a combination of both.

Finally, Boundary Condition 4, that of low planetary eccentricities and inclinations, is extremely important. The fact that all theorists explain this boundary condition can be seen from all the "yesses" in Table 9. Yet it is still not certain (after 300 years) that they are indeed boundary conditions on solar system origin, as assumed by the theorists (as opposed to evolution). If small inclinations and eccentricities could have been evolutionary, then, although present theories are not invalidated, a place is offered for (possibly radically) different classes of theory which arrive at eccentric or inclined planetary orbits at the time of planetary formation. Therefore, an important study would be to answer:

COULD THE PLANETS HAVE BEEN HIGHLY INCLINED OR ECCENTRIC AFTER THEIR FORMATION?

- Extensive computation, probably feasible now with fast computers, is required.

4.2 Progress Related Mostly to Controversial Parts of Theories

Theorists of the origin and evolution of the solar system differ most fundamentally on the following questions:

(1) Did the entire solar system originate from a single cloud, or did a pre-existing Sun capture part of an interstellar cloud which ultimately formed planets?

(2) If the single cloud theory is correct, how did the Sun lose or fail to acquire considerable angular momentum?

(3) Did planets grow from planetesimals or shrink from protoplanets?

Both single cloud contraction and cloud capture presently appear to be admissible starting points for a solar nebula.

Two new pieces of evidence can be useful in determining whether cloud capture is a likely process, however. First, the probability of the right kind of encounter of a star with an interstellar cloud might be determined. Secondly, the probability of a star like the Sun's having a planetary system might be estimated. The measurements required are:

THE SPATIAL DENSITY OF, AND CONDITIONS INSIDE INTERSTELLAR CLOUDS

and

THE FREQUENCY OF PLANETARY SYSTEMS.

- Extension of work in radio astronomy to higher spatial resolutions and sensitivities can probably yield satisfactory interstellar cloud properties. A breakthrough in technique, or very patient and very extensive observations will be required to obtain a satisfactory estimate of the frequency of planetary systems.

A real solution (or demonstration that a solution is impossible) to the fluid dynamics problem of single-cloud contraction would be very desirable at this time. It would be nice to know whether hydromagnetic forces or viscous forces are the more important, and whether the angular distribution in the solar system can be explained by either. Two ingredients are required for such a solution, initial conditions and correct calculation.

Likely initial conditions can be estimated from radio astronomical observations of interstellar cloud properties cited above, and by direct measurement of present-day

INTERSTELLAR DENSITY, TEMPERATURE AND MAGNETIC FIELD.

With known likely initial conditions it should be possible to compute the field properties of a collapsing cloud, using a minimum number of restrictions. In particular, hydromagnetic forces and some form of viscous forces arising from turbulence can be retained.

The third controversial question apparent from the theories is whether the planets were derived from planetesimals or from protoplanets. The remaining areas of new knowledge are useful in further understanding the mechanisms of accretion of planetesimals and evaporation from protoplanets as well as determining which is probably correct.

As has been discussed, Fowler, Greenstein and Hoyle show that presently observed isotopic ratios (Boundary Condition 12) can be explained by the presence of small (1-50 meter) planetesimals in the region of the terrestrial planets. If their theory is correct, then the Jovian planets, as well as comets, should have an entirely different set of isotopic ratios of lithium and boron, because of the large thermal-neutron-capturing hydrogen content there. Furthermore, they predict a different isotopic ratio of C^{13} to C^{12} than on Earth. A very significant measurement would be to obtain the

LIGHT ELEMENT ISOTOPIC RATIOS ON JUPITER AND/OR A COMET.

- A rather sophisticated spacecraft is probably required for the lithium and boron ratios. The $C^{13}:C^{12}$ ratio might be easier to obtain, though somewhat less definitive.

At present, the mechanism of accretion of planetesimals to form planets is not well understood. Asteroids appear to be fragments of larger primordial bodies, and so are not accreting; rather they are "unaccreting". Rain and snow accrete only to the size of hail, and no further. If accretion theories are to remain viable, some effort should be made to determine:

> THE CONDITIONS, IF ANY, UNDER WHICH PLANETESIMALS CAN ACCRETE TO FORM PLANETS.

- Continued study of high velocity impacts is probably a necessary ingredient of this determination.

The most noticeable problem in protoplanet theories is in (1) selectively getting rid of heavy volatile gases on a protoplanet (Boundary Condition 10), and (2) getting rid of anything on proto-Earth, Jupiter, Saturn, Uranus, and Neptune, all of which could have retained even hydrogen under postulated conditions of mass, and present-day exospheric temperatures (relevant to Boundary Condition 8).

Yet the mechanism of atmospheric escape is not known well enough at present to rule out substantial mass loss from protoplanets, even with modest exospheric temperatures. Furthermore, the estimate of exospheric temperatures given in Section 2 is very crude. It would be much better to obtain

THE EXOSPHERIC TEMPERATURE OF EACH PLANET.

- A thorough knowledge of upper atmospheric composition and scale heights would permit calculation of the exospheric temperature.

The escape rates from a planet have been calculated under the assumption that the base of the exosphere, which lies above the ionosphere on Earth, has a Maxwellian velocity distribution. There are reasons to criticize such an assumption when there are ionization processes nearby, and it is quite possible that the tail of the distribution function decreases with increasing velocity much slower than a Maxwellian. If so, atmospheric escape from protoplanets might be able to account for the problems cited above. Therefore, progress can be made by measuring

THE DISTRIBUTION OF VELOCITIES IN THE EXOSPHERE, AT LEAST OF EARTH.

- Satellite experiments are preferred.

The directions of future progress discussed in this section are summarized and evaluated in Table 10. There, the suggested work and its purpose is listed in the same order as in the above text. Priorities have been assigned on the basis of how much improvement man's knowledge of the solar system would be obtained with the particular area of future knowledge, independently of the difficulty in obtaining the required information. Unfortunately, it turns out that the easier and more straightforward measurements tend to be of low priority. The highest priority suggestions probably require very sophisticated spacecraft missions, such as a mission to solar system escape, and an atmospheric probe to Jupiter or rendezvous mission to a comet.

Table 10

DIRECTIONS OF FUTURE PROGRESS

	Relevant Knowledge	Specific Purpose	Overall Purpose	Priority
1.	The interstellar chemical and isotopic composition	Determine solar system raw material	Extend, modify, or reject present boundary conditions	Highest
2.	He:H ratio on the Jovian planets, especially Jupiter	Help determine early thermal history		High
3.	The evolution of stars in their pre-main-sequence phase	Solar conditions during and after planet formation		
4.	Xenon (and silver, if possible) isotopic ratios on planets, satellites, asteroids, comets	Date early solar system cooling		High
5.	The high density of Mercury	Determine silicate content of Mercury		Moderate
6.	The magnetic field properties of the planets	Input to planetary interior studies		Moderate
7.	The heat flux from lunar and planetary interiors			High
8.	The equation of state of iron-nickel, silicates, hydrogen under high pressure			Moderate
9.	Could the planets have been highly inclined or eccentric after their formation?	Remove low e,i as boundary condition on origin		High
10.	The spatial density of and conditions inside interstellar clouds	Determine probability of star-cloud encounter	Choose between cloud capture and single-cloud contraction (or neither) theories	Moderate
11.	The frequency of planetary systems	Measure of the probability of planets		Moderate
12.	Interstellar density, temperature, magnetic field	Give probable pre-solar system state of matter		High
13.	Cloud contraction theory	Solve angular momentum problem		High
14.	Light element isotopic ratios on Jupiter and/or a comet	Check prediction of Fowler, Greenstein, Hoyle	Choose between planetesimal and protoplanet theories	Highest
15.	The conditions, if any, under which planetesimals can accrete to form planets	Determine feasibility of accretion		High
16.	The exospheric temperatures of each planet	Help determine evaporation rates		Moderate
17.	The high velocity distribution of velocities in the exosphere, at least of Earth.	Help determine evaporation rates		Moderate

4.3 Mission Considerations

The space program can make a valuable contribution to understanding the origin and evolution of the solar system. Most of the areas of future investigation listed in Table 10 require spacecraft experimentation. It is clear, though, that there is no easy solution to the problems which really constitute barriers to our understanding of solar system origin and evolution.

Some of the proposed work involves a very wide range of targets, such as the determination of the magnetic field configuration of all the planets and the xenon isotopic ratios on planets, satellites, asteroids, and comets. Without at least a large sampling of solar system bodies using properly instrumented spacecraft, not much progress can be made in these areas.

On the other hand, some of the proposed work involves a restricted number of target or targets. Two such targets stand out as worthy of comment, Jupiter and the interstellar medium.

Referring to Table 10, there are 6 areas in which a properly instrumented mission to Jupiter can contribute (nos. 2, 4, 6, 7, 14, 16). Two of these areas (nos. 2 and 14) are related specifically to a Jovian planet, of which Jupiter is the most accessible, and one (no. 14) is one of the two areas of relevant knowledge that is assigned highest priority.

It appears, therefore, that early exploration of Jupiter ultimately leading to sophisticated missions capable of measuring isotopic ratios of lithium, boron, and carbon, would lead to a step function increase in our understanding the origin and evolution of the solar system. The end product of such an exploration program is likely to be the settling of the problem of planetesimals versus protoplanets, as well as the extension of some boundary conditions and the generation of others.

The interstellar medium is also a target of great importance. There are only two areas of relevance (nos. 1 and 12), but the first of these is of the highest priority. The chemical and isotopic composition of interstellar material is the standard to which the composition of solar system members should be compared. As we have seen, many of the boundary conditions summarized on page 55 are comparisons to a standard "cosmic" or other abundance (e.g. nos. 8, 9, 10, 11, 12 13 all involve such a comparison). A properly instrumented mission to the interstellar medium might alter the set of boundary conditions as presently constituted, and radically modify theories resulting from such an altered set of boundary conditions.

Appendix A

FLUID DYNAMICS OF CLOUD CONTRACTION

In this appendix we investigate some of the fluid dynamics involved in contraction of clouds of gas and dust leading to solar system formation. Five kinds of force and various combinations thereof are considered, though it is quite possible that not all are relevant to the formation of a solar system, and also that forces which are relevant are not included.

Consider the motion of a fluid element in a frame of reference which is rotating with a period equal to the period of rotation of the element. One can write an approximate equation of motion for the element in the following form:

$$D\vec{u}/Dt = \vec{F}_g + \vec{F}_c + \vec{F}_p + \vec{F}_v + \vec{F}_m \ ,$$

where the $\vec{F}$'s are the net force per unit mass on the fluid element, due to gravitational, centrifugal, pressure, viscous, and magnetic effects, subscripted g, c, p, v and m respectively.

The gravitational force $\vec{F}_g$ if given by $-\vec{\nabla}\phi$, where ϕ, the gravitational potential, is a function of the mass distribution in the cloud. For reasonable mass distributions the gravitational force is directed approximately toward the center of the cloud.

The centrifugal force, $\vec{F}_c$, which arises because we have chosen a rotating reference frame, is given by $-\omega \times (\omega \times r)$, where ω is the rotation rate of the frame and r the radius vector. The centrifugal force acts in a direction away from the rotation axis and is, therefore, essentially a repulsive force.

Today, bodies in the solar system are approximately in equilibrium between gravitational forces and rotational forces. Viewed in a rotating frame, the attraction by the Sun on a planet is balanced by the repulsion of the planets due to centrifugal forces, with corrections due to Coriolis forces, which are small for low-eccentricity orbits.

Pressure forces, which are given by $\vec{F}_p = \frac{1}{\rho}\vec{\nabla} p$, where p is the scalar (gas) pressure, are certainly important during the early stages of cloud collapse, and may also be significant at later times. Since the pressure is approximately proportional to the density and temperature of the gas, and since both density and temperature gradients tend to be positive toward the center of a cloud, the effect of pressure forces is to expand the cloud or to resist contraction.

Jeans (1929) has given a criterion for the stability of a uniform gas against gravitational collapse. The only forces considered are those due to gravitation, which tend to amplify any density disturbance, and those due to pressure, which tend to attenuate any pressure disturbance. Jeans considered sinusoidal perturbations in the uniform medium, and showed that small wavelength disturbances are damped out because pressure forces dominate, and large wavelength disturbances are amplified because gravitational forces dominate. The rate of growth is greatest for the longest wavelengths.

A further assumption is necessary in order to calculate the critical wavelength for collapse, one which involves the equation of state of the gas. If one assumes an adiabatic process, then it turns out that the critical wavelength for collapse is given by:

$$\lambda_o = \left[\frac{\pi \gamma c^2}{3 \rho G}\right]^{1/2}$$

where γ is the ratio of specific heats, c is the thermal speed (RMS) of the molecules, and G is the gravitational constant.

Most theorists employing cloud collapse as a start of the formation of the solar system assume that a perturbation in interstellar density grows due to a gravitational instability, leading to cloud collapse. Originally, the cloud had a small rotation (at a minimum, the rotation of the galaxy as a whole). Centrifugal forces are negligible at first, but as the cloud collapses very large rotation speeds can be obtained if each fluid element retains its original angular momentum. When the dimensions of the cloud are of the order of magnitude of the solar system, centrifugal forces can even exceed gravitational forces, leading to the shedding of rings of material from the cloud. If the cloud reached stellar dimensions without mass loss, the particle velocity in certain regions would approach the speed of light, and one would obtain a Sun with an exceedingly high rotation rate.

Two kinds of forces have been proposed to inhibit the rotation rate of the inner part of the cloud under contraction, or to slow the Sun's rotation speed after formation.

Viscous forces tend to reduce any velocity gradient in a gas. If the flow is laminar, then one can show that the ratio of viscous forces to pressure forces is approximately 1/R, where R is the Reynolds number, defined by

$$R = \frac{u\ell}{\nu},$$

where u is a typical flow velocity, ℓ is a dimension over which the flow speed changes by a significant factor, and ν is the kinematic viscosity. Taking u as 10 km/sec and $\hat{\ell}$ as 5 AU, one obtains a Reynolds number of 10^{21} for the solar system. This enormous value implies that ordinary viscous forces are negligible.

Recent (post-airplane) developments in fluid dynamics indicate that the above analysis is misleading, and that viscous forces may not be negligible. At large Reynolds numbers, the flow is turbulent, and one effect of the turbulence is to enhance effects of viscosity. For experimental flow situations at Reynolds numbers up to 10^8, it is known that one can approximate the behavior of a turbulent flow by increasing the viscosity coefficient from its original value to an amount greater by R/R_{crit} (Landau and Lifshitz 1959), where R_{crit} is the "critical" Reynolds number, i.e., the Reynolds number at which the gas makes a transition from laminar to turbulent flow.

Critical Reynolds numbers tend to be of the order of magnitude of 1000, which would imply that, for the cloud contracting in the solar system, viscous forces are smaller than pressure forces by a factor of 10^{-3}, not 10^{-21}. Being drag forces, they can exchange very large amounts of angular momentum from the Sun to the outer reaches of the solar system if allowed to act for a long duration.

If viscous forces are completely dominant, they would lead to a reduction in all velocity gradients, and imply that the solar system rotates as a rigid body. The Sun has a considerably larger rotation speed than the orbital speed of any of the planets. Therefore, turbulent viscosity might have been sufficient to slow the Sun down to its present rotation speed.

If the cloud has a sufficiently high electrical conductivity, then any magnetic fields present affect the fluid motions and must be included in the analysis. A hydromagnetic analysis is extremely complicated, though some simplifications can be made. If the ratio of pressure forces to magnetic forces is large (as it is in today's solar wind), then magnetic field lines tend to be entrained in the flow, and the flow is relatively unaffected by the field lines. If rotation is involved, the field lines are twisted into a spiral (Parker 1963), and apply a torque tending to straighten them out. The net effect is a "viscosity" which acts to prevent any velocity gradients perpendicular to the field lines. Magnetic forces impose a torque on the center of the cloud in the direction of a rigid rotation.

Various theorists, notably Alfven (1942, 1954) and Hoyle (1960), have considered the problem in some detail. They conclude, and later theorists concur, that early solar system conditions could have been favorable for large enough magnetic forces to distribute the angular momentum as it is now observed in the solar system.

To conclude, enough is presently known about the behavior of fluids to make plausible a theory of cloud collapse into a formation of a solar system. What would be very desirable is a real theoretical treatment of the entire problem of cloud collapse, from start to stellar formation, including viscous and magnetic forces cast in a physically justifiable fashion.

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