

N86-23505

INTERRELATIONSHIPS BETWEEN INTERSTELLAR AND INTERPLANETARY GRAINS

D. D. Clayton et al.

INTRODUCTORY REMARKS

No relationship between solar system "dust" (SSD) and interstellar dust particles (ISMD) can be taken for granted. The historical position has, for the most part, been that little or no relationship exists -- that SSD and meteorites come from collisions among bodies formed in the solar system from dust also formed from an initially gaseous solar nebula. Today that position is being rethought, spurred primarily by the discovery of isotopic anomalies in meteorites. It is unclear whether SSD has any relationship to the ISM or not. Our purpose then is to seek evidence for the extent of any existing relationships.

What one wants is a complete description of interstellar grains so that comparisons with well documented solar-system samples can lead by inference to the history that has produced the latter from the former. This is a lot to ask, but slowly the information can be assembled. Are interstellar grains chemically fractionated (e.g. Si separated from Fe) or are they rather well mixed, of roughly chondritic abundances? Do core-mantle structures record fractionation owing to thermal condensation sequences or are grains more amorphous? What is the composition and history of volatile mantles? What special isotopic components exist? For studies related to the origin of the solar system one may need to know the specific composition in molecular clouds, whereas for grains entering the solar system today one may require the properties of grains in a hot low-density shocked medium like that surrounding the solar system. To maintain some structure we will distinguish between these two major epochs that are under study.

I. INTERRELATIONSHIPS AT TIME OF SOLAR FORMATION

A. Meteoritic Record

Radioactive chronometers show that the meteorites assembled about 4.55×10^9 years ago, probably in association with the birth of the sun. Until about ten years ago, most meteoriticists assumed that the dust contained within the meteorites also had formed at that same time from an initially gaseous solar system. Following the discovery of isotopic anomalies there developed a view (Clayton, (1978) Moon and Planets, 19, 109) that severe isotopic and chemical fractionation of specific subclasses of presolar dust from others has left many "fingerprints" in the meteoritic record. This perspective succeeds the view of a nearby supernova admixing isotopic anomalies inhomogenously into the solar gas (Cameron and Truran (1977) Icarus, 30, 447 and most papers reporting isotopic anomalies). These "fingerprints" partially survived the chemical processes of transformation from submicron material to macroscopic minerals and breccias, leaving a chemical memory of their prior state that needs "developing" (as in film) by careful chemical experiments. To the extent that this interrelationship exists, it records conditions at that time rather than today, even though the chemical experiments are done today. The implied relationship is between interstellar dust and the processes of aggregation and chemical alteration that occurred within the forming solar system, probably in a turbulent accretion disk around the forming sun (Morfill and Volk (1984) Astrophys. J., 287, 371; Cameron (1978) Moon and Planets, 18, 5; Lin (1981) Astrophys. J., 246, 972). In this general theory of the meteoritic record, one does not expect to find ISMD per se, but rather effects remembered when it is fused into new forms. The ways in which this might have happened are frontier research areas.

What one sees today (primarily from isotopic anomalies) are clues that a relationship existed 4.55×10^9 yr ago between ISMD and the SSD of that era which aggregated into the parent bodies of the meteorites. Conceptually one can distinguish between the relationship of SSD to ISMD and the relation of SSD to Circumstellar dust. Because the experimental evidence relating to this interrelationship is primarily chemical, the thread being sought is that of

chemical memory from source to meteorite (Clayton (1982) (Q. J. Roy. Astron. Soc. 23, 174)). To clearly envision ISMD/SSD interrelations, it is first advisable to identify the more dramatic circumstellar/SSD connections, because it is they that attest to the entire cosmic chemical memory. The following circumstellar/meteoritic connections are not offered to "explain" more complicated meteoritic situations, but rather to highlight the excitement of well documented isotopic patterns that may be rationalized by nucleosynthesis and stellar condensation. This excitement was the direct result of dozens of experimental discoveries by meteoritic chemists over the past dozen years. It will not be our intent to document all of these in what follows, but rather to point to especially clear treatments.

A.1 Circumstellar/Meteoritic

Many observable chemical properties of meteorites seem to have first been established during mass loss from stars. Condensation in the outflow can freeze circumstellar material before it mixes with the ISM, freezing an anomaly while it is still quite large. Two stages of processing, one in the ISM and one in the processes of solar aggregation, will have modified these materials.

i) Isotopic Connections (Circumstellar)

Because dust is expected to condense in stellar outflows, even of supernovae (Hoyle and Wickramasinghe, 1970 Nature, 226, 62; Clayton, 1975 Nature, 257, 36) and novae (Geisel et al., 1970 Ap. J. (Letters), 161, L101; Clayton and Hoyle, 1976 Astrophys. J., 203, 490; Clayton and Wickramasinghe, 1976 Astrophys. Spa. Sci., 42, 463), isotopic structures specific to the star and even to specific radial zones of the star may be trapped within that dust and offer an explanation for the origin of many isotopically anomalous materials. Key examples of this circumstellar/meteoritic connection are:

(a) Ne-E, an almost isotopically pure ^{22}Ne component identifiable as a specific gas release from certain meteoritic samples (Black, Geochim. Cosmochim. Acta, 36, 377 (1972); Eberhardt et al., 1979 Astrophys. J. (Letters),

234, L169; Lewis et al., 1979 Astrophys. J. (Lett.), 234, 165). Clayton (1975, Nature, 257, 36) suggested that sodium condensed in nova and supernova effluent and that these grains, enriched in ^{22}Ne after condensation by ^{22}Na decay during the next several years, could carry a ^{22}Ne component in ISMD. Although no other explanation seems to produce such a high-purity sample of ^{22}Ne , it cannot be concluded merely by default that this source is the correct one. Still needed are definitive descriptions of the meteoritic carriers and the way they evolved from the circumstellar carriers.

(b) ^{16}O , a monotopic excess of up to 5% in anhydrous minerals from Allende inclusions and other related objects. In their discovery paper R. Clayton et al. (1973, Science, 182, 485) speculated that the ^{16}O -excess came from interstellar grains with a nucleosynthetic history different from average solar system material, while D. Clayton (1975, Astrophys. J., 199, 765; 1977 Icarus, 32, 255, 1978 op. cit.) argued instead that condensation in the outflow of a supernova interior was necessary. Later Cameron and Truran (1977 Icarus, 30, 447) interpreted the available observations as an inhomogeneous spatial admixture of newly synthesized ^{16}O from a supernova trigger to solar birth. One current model is that the supernova condensates (SUNOCONS) created ^{16}O -rich refractory grains, thereby establishing a generic line to the refractory ^{16}O -rich meteoritic minerals. That spinel (MgAl_2O_4) is the most ^{16}O -enriched of all interstellar minerals is predicted by the SUNOCON theory, since that mineral is predicted to be the major condensate of the carbon-burning ejecta (Clayton 1977, Earth Planet. Sci. Lett., 35, 398; Lattimer et al., 1978 Astrophys. J., 219, 230). However, it does not follow that the spinels as found in meteorites are themselves SUNOCONS, or even that the spinel agreement is more than a coincidence; more likely the SUNOCONS were nucleation sites for growth or amalgamation of macroscopic spinels in the secondary mineralization processes occurring in the solar nebula. R. Clayton (1984 Protostars and Planets II, Tucson) has described what the meteoritic evidence seems to suggest. This theory also predicts that refractory interstellar dust must be more ^{16}O -rich in bulk than is interstellar gas, a useful feature of models of later exchange of oxygen (R. Clayton and Mayeda (1977) Geophys. Res. Lett., 4, 295; Wood, 1981 EPSL 56, 32).

(c) Xe-HL, once called "carbonaceous chondrite fission (CCF) xenon" and sometimes referred to as Xe-X. Lewis et al. (1975 Science, 190, 1251) made a great innovation by chemically separating via acid dissolution the microscopic portions of meteorites that carry this Heavy-isotope-rich and Light-isotope-rich component of anomalous xenon. The name CCF xenon has largely been discarded after Manuel et al. (1972 Nature, 240, 99) showed that the associated light-isotope excess could not be fission xenon, so that a name involving fission xenon would not seem appropriate. They suggested the name Xe-X and also suggested that a mixture of r-process xenon and p-process xenon, which bears a similarity to Xe-X, could have been ejected into the solar system by a nearby supernova. Clayton (1975, Ap. J., 199, 765; 1976 Geochim. Cosmochim. Acta, 40, 563) preferred condensation within SUNOCONS; Black (1975 Nature, 253, 417) advanced a similar interpretation. SUNOCONS greatly shortened the range of half lives of fissioning nuclei that could have contributed to a fission component. Subsequent experimental studies by Lewis et al. (Nature, 305, 767 (1983); Science, 222, 1013 (1983)) demonstrated that in situ fission, that is to say, fission within the meteorite in its present form, is no longer a viable alternative. Neither the nuclear origin nor the history of this component has been pinned down, but some involvement with circumstellar dust seems to be involved on general grounds. A promising picture is high speed implantation in circumstellar carbon grains. (Clayton (1981) Proc. Lunar Planet. Sci., 12B, 1781). In a more popular account, Lewis and Anders (Scientific American, 249, 66 (1983)) have stressed experimental evidence for the connection between this component of anomalous xenon and grains of carbon, which are presumably interstellar.

(d) Xe-s, or s-process xenon. In acid residues from the Murchison meteorite, Srinivasan and Anders (1978, Science, 201, 51; Lewis et al., 1979 op.cit.) found clear evidence of some chemical carriers that had trapped s-process xenon before it could mix with ISM gas. Condensation of carbonaceous carriers in red giant (C star, S star) atmospheres seems indicated. This possibility had previously been predicted in a paper submitted for publication in 1975 (Clayton and Ward, Astrophys. J., 224, 1000 (1978)). What Clayton and Ward (1978) argued is very simple and general: because the fractions of xenon condensing into grains could not have accidentally been identical for s-

process events and r-process events, any subsequent mechanical variations in the interstellar dust/gas ratio must be associated with corresponding s/r fractionations in the heavy isotopes of a given element. This single diagnostic should find many applications as experimental resolution continues to improve. But in the case of Xe-s, the observations could be taken even further by Swart et al. (Science, 220, 406 (1983)), who showed that it is carried in carbonaceous material having about twice as much ^{13}C as terrestrial carbon.

(e) Neodymium decomposition. In addition to clearing up some important questions for nucleosynthesis theory, the recent measurements of the neutron-capture cross sections of Nd by Mathews and Kappeler (Astrophys. J., 286, 810 (1984)) bring two relationships between Circumstellar and meteoritic dust into clearer focus. The first is a confirmation that the isotopic pattern of Nd found in acid resistant residues (therefore carried in a carbonaceous component) of the Allende meteorite measured by Lugmair et al. (1983 Lunar Planet. Sci., 14, 448) does indeed fit the s-process pattern if the sample carries the isotopic fractionation suggested by Clayton (1983 Astrophys. J. (Letters), 271, L101). If so, this Nd pattern is similar to that of s-process Xe, but it is the first s-process pattern identified in a refractory element. The neutron cross sections also confirm that the Nd pattern in the FUN Allende inclusion EK1-4-1 (McCulloch and Wasserburg, 1978 Astrophys. J. (Letters), 220, L15) appears to be a simple excess of the r-process isotopes averaged over nucleosynthesis events in the same way that bulk solar matter itself has. Identification with average r-process abundances speaks against (Clayton (1978) Astrophys. J., 224, 1007) a neighboring supernova injection and in favor of a chemical-memory fractionation of the ISM, perhaps even by gas/dust fractionation but also perhaps by r-dust/s-dust fractionation. What can be said without controversy is that continuing measurements of isotopically anomalous samples will be invaluable in the search to identify the chemical memory involved. Decomposition of Sm isotopes confirmed this same interpretation (Lugmair, Marti and Scheinin, 1978, Lunar and Planet Sci., 9, 672; Clayton, 1979 EPSL, 42, 7; Lugmair et al., 1983, Science, 222, 1015).

(f) Extinct refractory anomalies in SUNOCONs. Clayton (1975 Nature, 257, 36) argued from the theory of nucleosynthesis that refractory SUNOCONs should condense some key nuclei as short-lived progenitors. He especially singled out ^{41}K (via ^{41}Ca) and ^{44}Ca (via ^{44}Ti) as targets of study (see also 1977 EPSL, 36, 381). Although neither prediction has yet been confirmed, tantalizing hints exist in published data. A specific ^{44}Ca anomaly would be especially valuable because its progenitor is, like that of Ne-E, much too short-lived to exist in the interstellar medium or solar system, so that an incontrovertible circumstellar/interplanetary connection would be indicated. The special case of extinct ^{26}Al , predicted to compete with live ^{26}Al as a source of excess ^{26}Mg , receives special attention in the next section.

(g) Interstellar ^{26}Al and excess ^{26}Mg . When groups in Australia and Caltech (Gray and Compston, 1974 Nature, 251, 495; Lee et al., 1977 Astrophys. J. (Letters), 211, L107) first showed that aluminum-rich minerals within the Ca Al-rich inclusions (CAI's) from the Allende meteorite carried an excess of the heaviest isotope of magnesium, ^{26}Mg , it was concluded by some meteorit-icists that a supernova explosion beside the forming solar system must have peppered the solar cloud with radioactive ^{26}Al . This model has been shaken by the detection of radioactive ^{26}Al in the interstellar medium today. The historic first detection of interstellar radioactivity was made by the HEAO 3 spacecraft (Mahoney et al., 1984, Astrophys. J., 286, 578) which recorded a measurable flux of 1809 keV gamma rays striking the solar system. The 1809 keV gamma rays are well known signatures given off following the beta decay of an ^{26}Al nucleus. The HEAO 3 measurements indicate that about 4.8 such gamma rays impact a square meter in the solar system every second, and come from the general direction of the center of our Galaxy. Any lingering doubts about the reality of this astonishing discovery have now been removed by a confirmation using the Solar Maximum Mission that was so dramatically repaired by the Shuttle astronauts and which carried a gamma ray spectrometer that had since February 1980 taken unintentional periodic looks at our Galactic center. That spectrometer team (Share et al., 1985, submitted to Astrophys. J.) confirms a flux of about 4.0 gamma rays per square meter per second from the general direction of the Galactic center, in direct agreement with the HEAO 3 measure-

ment. It can now be asserted without reasonable doubt that some source of radioactive ^{26}Al lies in the general direction of the galactic center.

The analysis of the magnitude of this gamma ray flux and its implications for both the origin of the elements in explosions of stars and for the origin of the Allende minerals was undertaken by Clayton (1984, Astrophys. J., 280, 144) who concluded: (1) if the ^{26}Al is spread uniformly throughout the interstellar gas, its concentration of about 10 parts per million of aluminum is rather close to the fossil evidence found in Allende minerals, suggesting that the requirement of a special supernova trigger to solar formation may have been unnecessary; (2) supernova explosions are not adequate to maintain this average level of interstellar radioactivity, so that nova explosions or gas streaming away from giant stars are the more likely origins of the radioactive aluminum. The ineffectiveness of supernovae in maintaining the observed interstellar concentration also argues against implicating a specific supernova with the solar origin. Cameron now argues (Icarus, 60, 416 (1984)) that wind from an asymptotic giant branch star of about one solar mass carried ample ^{26}Al along with it and participated hydrodynamically in the formation of a molecular cloud core wherein the sun formed. Interpretation of the excess ^{26}Mg in Allende aluminum-rich minerals depends upon the correct interpretation of the ^{26}Al gamma ray line, which requires better information on the angular distribution of the gamma rays. Because of wide viewing angles the HEAO 3 and Solar Maximum Mission teams can not be very precise about the angular distribution. Although it is "consistent with" radioactivity concentrated in the galactic plane having peak intensity near the Galactic center, the data might not require that interpretation. A single recent supernova toward the general Galactic center would occupy a large circular area on the sky; however it would be most unlikely that the center of such a nearby distribution would happen to lie in the plane of the Galaxy. If the observing teams can successfully show that the latitude distribution is narrow and centered on the plane, we will be forced to accept the interpretation that the observed ^{26}Al concentration is a general feature of the interstellar gas.

The interstellar isotopic concentration ($^{26}\text{Al}/^{27}\text{Al} = 10$ parts per million) lies squarely between but distinct from the concentration of 50 parts

per million seen in some, but not all, aluminum-rich Allende minerals (Lee et al., 1977 op. cit.) and the much smaller concentration (less than 1 part per million) that could be maintained there by supernova explosions. Thus the observed Allende concentrations of excess ^{26}Mg are still too large to be interpreted as being the average interstellar concentration. If the ^{26}Al was actually once alive in the Allende minerals seen today there must have been some source of ^{26}Al enhancement in the solar cloud as it was collapsing to form the solar system. This is the reinterpretation that Cameron now advances and which is consistent with a common meteoritic interpretation that the ^{26}Al was alive in the minerals at the time of their formation.

Whatever the source of the ^{26}Al observed today, those objects are necessarily ejecting $4 M_{\odot}$ per million years into the interstellar medium. By contrast supernova eject $24 M_{\odot}$ of new stable aluminum and stars reinject $60 M_{\odot}$ of old stable aluminum over the same million years. Arguing that all of these ejecta condense into refractory aluminum-rich solids as they leave their respective sources, that the ^{26}Al decays to ^{26}Mg within the resulting mixture of well mixed dust grains, Clayton reasoned that the ratio $^{26}\text{Mg}/\text{Al} = 0.04$ results within the aluminum-rich dust. This high interstellar correlation of excess ^{26}Mg with Al could not have been totally removed by evaporation, because the Allende minerals carry other isotopic anomalies that demonstrate that they were not evaporated totally at any stage prior to their assembly. Thus, the ^{26}Mg -Al correlation observed in Allende minerals may be a manifestation of a cosmic chemical memory (Clayton (1985) Geophys. Res Letters submitted).

At the present time, it is still uncertain whether the ^{26}Al was alive in situ or if it is primarily or partly a fossil. The data may well reflect both aspects. Paradoxically the gamma ray observations have raised the plausibility of both options! Searches for other extinct radioactivities, especially ^{41}Ca , ^{53}Mn and ^{60}Fe are badly needed and are in progress (R. Clayton, personal communication), because their presence or absence may point the way to the correct interpretation. This entire issue remains one of the most significant controversies about possible interrelations of circumstellar dust and meteoritic aggregates.

ii) Chemical Fractionations (Circumstellar)

It has been common to believe that thermal condensation sequences produce the same minerals that they would in thermal and chemical equilibrium, even during supernova expansions (e.g., Lattimer et al., 1978 *op. cit.*). If that assumption were true, it would imply that virtually all of the dust that has been ejected from the stars exists in refractory condensation sequences, so that the interstellar medium would be heavily fractionated with respect to these refractory elements. (Note: "fractionated" in this chemical context implies only that the elements are not microscopically mixed in their cosmic abundance ratios (e.g., Si/Fe=1), but instead reside in chemical structures (e.g., MgSiO₃) that have fractionated them microscopically. It is not taken to mean that averages over large volumes have variable abundances, although that too many occur for dynamical reasons.) If the elements are microscopically fractionated in the circumstellar origin of ISMD, the SSD will in part remember that fractionation, perhaps even in macroscopic meteoritic samples (Clayton and Ramadurai, 1977, *Nature*, 265, 427). However, simplistic models of circumstellar grain formation which rely on the attainment of "equilibrium" in the turbulent ejecta of stars undergoing mass loss have often been criticized by Donn (e.g. 1978, *Protostars and Planets*, 100-111). Specifically, Nuth and Donn (1981, *Astrophys. J.*, 247, 925) have shown that thermal equilibrium is not attained in such regions due to cooling via molecular radiation while Donn and Nuth (1985, *Astrophys. J.*, 288, 187) demonstrated that even nucleation theory can not be successfully applied to this process. Detailed grain models based on "equilibrium condensation" in stellar sources therefore seem rather implausible. The challenge in the present context of interrelationships between ISMD and meteoritic material is to find and describe realistic condensation and aggregation histories that map ISMD chemical fractionation onto meteoritic fractionation. This can be illustrated as a question: Does the tendency for meteoritic Mg to exist in oxides while Fe exists in metal and sulfides have any connection to the corresponding SUNOCON fractionation, or have those meteoritic fractionations been established in the solar system itself? That question is then generalized to others of a similar nature.

The reader must be reminded that one interrelation may, but need not, imply another. For example, there may exist a connection between CIRCUMSTELLAR/INTERSTELLAR fractionation patterns without the existence of the corresponding relation to SSD fractionation patterns - for example if the SSD patterns were all established in the solar system without memory of prior fractionation. Isotopic systematics argue against that particular scenario, but admitting its possibility may help clarify often fuzzy distinctions.

A.2 Interstellar/Meteoritic

Section A.1 demonstrated the clear evidence for the survival of circumstellar signatures in meteoritic dust. With that backdrop one can ask about the ISMD/meteoritic connection, which has been controversial and hard to pin down.

i) Some ISMD must survive the origin of the solar system

This raises the question of just how much ISMD, and which part of it, has survived and to what degree it has remained unaltered. The minimum requirement would seem to be that at least part has survived until at least a portion of it has been aggregated into larger accumulations so that its isotopic fingerprints remain on the final product even after some metamorphosis. A much stronger definition of survival, and therefore a less likely version, would be that interstellar dust particles themselves remain imbedded in meteorites. Between these extremes lies a spectrum of degrees of partial survival. This is a frontier research question. That the amount of unhomogenized material is large is attested to by macroscopic aggregates having 5% excess of ^{16}O and 10% excess of ^{50}Ti (Fahey et al, Lunar Planet. Sci., 16, 229 (1985)). However, suggestions that isotopic fractionation by distillation may have produced these anomalies still exist (Esat, Spear and Taylor, Lunar Planet. Sci., 16, 217 (1985)).

The principal observational evidence for the presence of some interstellar, as distinct from circumstellar, material in meteorites lies in the very high D/H values measured in several organic fractions of carbonaceous and

other primitive chondrites (e.g. Robert and Epstein, 1982). Enrichments in D of up to a factor of about 35 relative to the galactic value are observed. The only known mechanism capable of generating such an enrichment is the isotopic fractionation associated with ion-molecule reactions taking place at very low translational temperatures. Such reactions are inferred to be responsible for the even larger D enrichments observed astronomically in molecular clouds (e.g. Watson et al., 1977). Consequently, the idea has become widely accepted that at least part of the D found in primitive meteorites stems from molecules formed in such interstellar clouds (Geiss and Reeves, 1981, *Astron. Astrophys.*, 93, 189; Kerridge, 1983, *EPSL*, 64, 186). Note, however, that to a certain extent this is an argument by default; a more rigorous observational connection between meteoritic organic matter and interstellar chemistry would be most desirable.

Recently a new set of fine-grained primitive extraterrestrial materials has become available through stratospheric dust collections of which the most challenging subset is formed by chondritic Interplanetary Dust Particles (IDP's) (Brownlee et al., 1977; Fraundorf et al., 1982; Mackinnon et al., 1982). The morphology of chondritic IDP's varies from non-porous to highly porous, fluffy particles commonly referred to as Chondritic Porous (CP) IDP's (Rietmeijer, 1985). The large D/H fractionation ratios of many chondritic IDP's (Zinner et al., 1983) suggest that this new class of extraterrestrial materials may be more primitive than the primitive (carbonaceous) chondrite meteorites.

Chondritic, including CP, IDP's are essentially cosmic sediments in the sense suggested by Wilkening (1978) and McSween (1979) for matrices of carbonaceous chondrites. The IDP's are heterogeneous, non-equilibrium mixtures of high- and low-temperature minerals (cf. Wood et al., this volume). Of the varied mineralogy of these IDP's, summarized in McKay et al. (1985), grains of Bismuth metal (Mackinnon and Rietmeijer, 1984), Titanium metal (Mackinnon and Rietmeijer, 1983) and single crystals of Tin or Tin dioxide (SnO_2) (Fraundorf, 1981; Rietmeijer and Mackinnon, 1984) and Titanium-oxides (Rietmeijer and Mackinnon, 1984) underline the very primitive nature of IDP's since these minerals appear to be absent in carbonaceous chondrites. These minerals sug-

gest that chondritic IDP's provide a window through which we may view individual remnant ISMD grains which, even in the carbonaceous chondrites, may already have lost their identity through metamorphosis (Rietmeijer, 1985).

ii) A specific and correct theory for the aggregation of ISMD (where and when) and for the environment (especially thermal) of those aggregates is needed to evaluate survival scenarios. Therefore, a continuing strong research emphasis must be on the physics and chemistry of aggregation.

Some aggregation may occur in the turbulent ISM itself. These aggregates will form cold. Aggregation could occur in the "mother" molecular cloud or in prior history. It is exactly at this point that one desires a complete description of the chemical constitution of the dust in the molecular cloud. Every detail of the chemical history will have to be followed in some statistical sense, and occasionally in an explicit sense. This formidable problem no doubt requires ISM dust science and meteoritic science to proceed iteratively.

Some aggregation may occur in the collapse of a turbulent cloud to a protosolar disk (Cameron, 1975 Icarus, 24, 128). Chondrule sized (0.1 mm) bodies may be aggregated in profusion at this time accompanied by a significant rise in the temperature of grain aggregates. Aggregation in the solar accretion disk itself might occur subsequently. Model calculations exist (Volk et al., 1978 Moon and Planets, 19, 221; Morfill and Volk, 1984 Astrophys. J., 287, 371). Chondrule-sized objects are indicated.

Conventional wisdom among meteoriticists is that the components of chondrites (chondrules, CAIs, matrix dust) were formed in a wide variety of places and temperature regimes, after which they mixed into cm-size aggregations which had enough mass to sink to the nebular midplane. There the dust-rich layer became gravitationally unstable, and aggregation into planetsimals began. Wood (1985a, b) however, has argued from the absence of preserved cm-size structures in chondrites that this particular stage of coalescence did not occur. He also argues from the fact that various chondrite subtypes contain distinctive types of chondrules (etc.) which did not mix with one another

prior to accretion, that in fact chondrite aggregation must have occurred very promptly after the high-temperature events or processes that created the chondrules, probably within a few orbital periods. A manifestation of gravitational instability seems required that does not require concentration of the chondritic solids at the nebular midplane.

Certain observations allow constraints to be placed on the manner in which processed grains aggregated into meteorites in the intermediate parts of the solar nebula. The first of those observations is that each different type of chondritic meteorite consists of components (CAIs, chondrules, matrix) that are usually different from those in other types e.g. (CAIs that are coarse-grained and centimeter-sized are found only in CV chondrites such as Allende, while ferromagnesian chondrules (though almost universally present) differ in composition and size range in the CV, CO, CM, CI, enstatite and ordinary chondrites. There was therefore, very little cross-mixing of components between the different chondrite formation regions. The only escape from this conclusion would be if the ingredients are altered by the cross-mixing; that is, if the ambient temperature and chemistry alter each ingredient as it migrates from region to region. On the other hand, some common chondrule types are apparently indistinguishable whether they occur in CM, CV, ordinary or enstatite chondrites (Scott and Taylor JGR, 88, B275 (1983)).

A second observation is that the main belt asteroids (the probable source of meteorites) are stratified into a series of concentric zones which change systematically in composition outwards from Type E at 2 AU to Type S to Type C to Type D at 5 AU (Gradie and Tedesco, 1982).

A third observation is that all of the various chondrite types, though made up of quite different components, nevertheless contain approximately solar relative proportions of non-volatile elements. This suggests that the various chondrite types formed as separate, almost closed, systems and is consistent with the absence of cross-mixing noted above.

A fourth and very important observation is that all chondrites have some components (CAIs, chondrules) that were made at high temperature ($>1000^{\circ}\text{C}$) and

then cooled within minutes to days (Paque and Stolper, 1983; Hewins, 1983). This requires the high temperature regions to be of quite limited volume and/or duration. It also suggests that solar radiation was not the heat source. Taken together with the earlier observations, it further indicates that refractory components were not made near the sun and transported outwards by turbulence.

The fifth and final observation is that the various components are randomly mixed within each meteorite. This means that formed components were placed into "parking" orbits where they mixed with other components but did not clump together to produce the meteorite parent body until after all its components had been formed.

Aggregation of parent bodies from planetesimals occurs subsequently. A huge literature exists (e.g. Hayashi et al., 1984 in Protostars and Planets II). This more-or-less standard theory relies on larger bodies gathering smaller ones by collisions during the collisional evolution of the disk; but alternate ideas exist.

A detailed "hydromagnetic-planetesimal" model for the agglomeration of larger bodies from smaller bodies around a magnetized spinning body (either the sun or a planet) has been developed by Alfvén (1954) and subsequently extended by Alfvén and Arrhenius (1975). In this model the hydromagnetic transfer of angular momentum from the magnetized, spinning central body to the surrounding, infalling, dusty plasma results in the formation of a circum-solar or circum-planetary disc in the equatorial plane. There are several mechanisms proposed for the spontaneous radial break-up of this disc into concentric tori. If the collisions between dust grains within each of these tori were sufficiently "sticky", they would lead to the gradual formation of larger bodies in the equatorial plane. A similar idea of inelastic collisions between bodies in nearly identical orbits leading to larger bodies, has also been discussed by Safronov (1967).

iii) The thermal history of aggregates must be known to evaluate the loss of volatiles and all subsequent metamorphism. A specially interesting

problem is the origin of chondrules. What are the sources of heating that must be evaluated? Many have been suggested, but the following look most relevant, in chronological sequence of their possible occurrence.

(a) Cold interstellar aggregates may be heated by aerodynamic drag after passing through the standing gas shock associated with the supersonic infall of matter toward a solar disk (Wood, 1984 EPSL, 70, 11). Wood assumes an infall speed of 10 km/sec dissipated as dust falls onto the nebular disk. The subsequent chemistry and aggregation deserves much study. Interstellar grains and grain aggregates would not be stopped at the shock front of course, but would continue through the decelerated gas at (initially) the prenebular infall velocity; e.g. on the order of 10 km/sec. Aerodynamic drag would decelerate and heat the grains. Wood (1984) has identified conditions under which drag heating could turn interstellar dust into chondrules and CAIs. The effect appears to be important only where dust-enriched parcels of interstellar gas impact the solar nebula: in the absence of an optically thick environment near the nebula surface (such as a high concentration of dust would provide) drag-decelerated objects would cool too efficiently by radiation to be heated significantly. A corollary of this situation is that some interstellar grains (e.g. - those which did not enter the nebula in dust-rich ensembles) would not be heated, and might still retain their interstellar properties when incorporated in chondritic planetesimals.

(b) Exothermic chemical heating occurs whenever highly disequibrated aggregates are heated sufficiently to trigger the exothermic rearrangement. Clayton (1980, Astrophys. J. (Letters), 239, L37) has suggested this as a heating source capable of both chondrule formation and thermal metamorphism of small planetesimals. Aggregation of chondrule-sized clumps would have to occur in such a way that the clump remained cold enough that its chemical rearrangement not be triggered. Such dust aggregates might subsequently be heated by ambient temperatures in the accretion disk, at which point chemical runaway could occur.

(c) The ambient gas temperature within the solar accretion disk could be high enough to thermally anneal amorphous grains or even vaporize presolar

materials. The source of this heat is the "frictional" dissipation associated with viscosity and the outward transport of angular momentum (e.g. Lin 1981 op. cit.; Morfill and Volk (1984) op. cit.). The highest temperatures (>1000K) lie closest to the sun with colder temperatures (<500K) in the likely regions of meteoritic accumulation. Dust aggregates may be turbulently transported between these regions by a radial random walk (Morfill and Volk, 1984 op. cit.). This situation raises the possibility of adding to parent bodies dust aggregates having a wide spectrum of thermal histories. In this model the aggregation history and the thermal history are coupled problems. But if it is to be effective, this radial mixing from regions of different temperature must circumvent the chemical arguments against mixing detailed above by allowing the aggregates to alter during transport.

(d) Lightning strokes may heat selected portions of the disk.

(e) Ohmic dissipation resulting from motion through magnetic fields could heat larger bodies over hundreds of thousands of years.

(f) Parent-body heating and alteration may occur after its accumulation either by trapped heat, by radioactive energy release, or by chemical energy release. These stages of thermal metamorphism are a significant part of meteoritical science (c.f. Meteorites, R. T. Dodd, Cambridge University Press 1981, Chapter 6, or the meteorite section of this report). Some meteorites (chondrites) are magmatically differentiated by this process, and some have been altered by "geothermal" fluids.

iv) Nonthermal effects on presolar grains must be evaluated for tracers that can reveal something of the time spent in the ISM.

a) Sputtering of small refractory grains may be expected to produce an isotopic fractionation between the fraction of the element remaining in the grains and the fraction in the interstellar gas. Clayton (1981, Astrophys. J., 251, 374) has advanced this as the mechanism for producing the large isotopic fractionation found in certain anomalous Allende inclusions. A more detailed scenario for this fractionation is needed. The basic idea is that as

sputtering grinds grains down to their most refractory centers it also establishes a skin depth that is isotopically fractionated. On general grounds one expects light isotopes to be removed somewhat preferentially by the sputtering. If the element is very refractory, so that it resides overwhelmingly in grains, the pool of gas phase isotopes may be considerably lighter than the condensed portion. Mechanical separation of dust from gas, or of sputtered skins from interiors, can result in bulk isotopic fractionation. One way of mapping this onto a chemical memory is to recondense the gas onto small grains, employing grain-size effects to produce bulk macroscopic isotopic fractionations (Clayton, 1980 EPSL, 47, 199).

The sputtering of sequentially condensed refractory elements may also play a key role in maintaining a higher gas concentration of less refractory elements. The most refractory elements remain most shielded from sputtering. For example, the fraction of Al in ISM gas may be much less than the fraction of Mg because the Al is not nearly as exposed to sputtering as Mg is. Although the related phenomena are difficult to observe in the astronomical setting, they may define important relationships between ISMD and meteoritic dust.

b) Cosmic rays cause spallation reactions within grains. These may produce isotopic anomalies (Ray and Volk, 1983 Icarus, 54, 406). Heavy cosmic ray nuclei also leave ion tracks that may be exposed by etching. A large literature exists for study of these effects during solar system history, but the presolar component is harder to identify.

c) Higher speed grain-grain collisions ($v > 1$ km/sec) are normally thought to be disruptive to grains. But is it possible, if ISMD has a composite structure containing both refractory components and mantles, that clumps of larger refractory-rich aggregates can be grown in violently turbulent settings. Clayton (1977 EPSL, 35, 398; 1981 Astrophys. J., 251, 374) has argued that this scenario could conceivably prepare parents of the CAI's. Elmeegreen (1982 Astrophys. J., 251, 820) has argued that this could come about in the wake of ISM supernova shock waves, where ample sputtering will also be expected.

The major dust processing agents in the interstellar medium are interstellar shocks. The average dust grain has passed through one to ten 100 km-s^{-1} interstellar shock waves. In each of these shock waves, a grain composed of N atoms is struck by $10 N$ protons, $N \text{ He}^+$ and He^{++} ions, and perhaps $10^{-2} N$ carbon, oxygen and nitrogen ions, with kinetic energies of order $100 m \text{ eV}$ (where m is the mass in atomic units of the ion). These ions both sputter the surface of the grain and are implanted in the grains. The former process may cause some small degree of isotopic or chemical fractionation as lighter atoms or more weakly bound atoms preferentially sputter. The latter process may make the grains (or their surfaces) resemble lunar surfaces which have been exposed to the solar wind. In addition, in each shock wave a typical grain is struck by smaller grains with relative velocities of $5\text{-}100 \text{ km-s}^{-1}$. The more energetic collisions could certainly result in vaporization and shattering. The less energetic collisions may lead to cratering of the larger particle. The vapor may later be redeposited on colder interstellar grains, causing a distinct mantle or surface layer to appear on the grain. **Thus, an interstellar grain may be recognizable because it has been sputtered, ion implanted, cratered, and mantled.**

Grain-grain collisions play an important role everywhere there are grains present. Low velocity impacts ($v \ll 1 \text{ km/s}$) generally lead to accretion of both particles. This effect plays a major role in the early nebular disk, and at the present time in dense planetary rings. The relative speeds in the latter case are in the range of cm/s . However, recent laboratory experiments with impacts of projectiles into low density materials (i.e. $\ll 1 \text{ g/cm}^3$, like styrofoam) by Werle, Fechtig and Schneider (1981, Proc. Lunar Planet. Sci., 12B, 1641) show that a major fraction of the impacting body can be recovered almost intact even at speeds as high as 6 km/s . This speed is not an upper limit but is simply the maximum speed at which the experiments were performed. This situation may be important for the capture of interstellar particles in low density snow on the surface of comets in the outer solar system, where relative speeds are at a minimum.

High speed collisions ($v \gg 1 \text{ km/s}$) generally lead to the destruction at least of the smaller of the two colliding particles. The effects are based on

laboratory experiments which were described by Gault and Wedekind (1969, JGR, 74, 6780), Gault (1973, The Moon, 6, 32) and Fujiwara et al. (1977, Icarus, 37, 277). These experiments were performed with mm-sized projectiles at speeds below 10 km/s onto glass, rock and metal targets. Experiments at higher speeds (>20 km/s) with micron-sized particles are described by Hörz et al. (1975, Planet. Space Sci., 23, 151). The latter experiments primarily studied cratering and therefore, pertain to erosion of the larger body.

High speed collisions between two particles lead to the destruction (evaporation) of the smaller of the two particles while the larger one may be just cratered or fragmented. In the first case the excavated material will be solid particles, to a smaller extent liquid droplets and only the order of the small particle mass will be evaporated. The total mass excavated (i.e. the crater volume) depends on the kinetic energy of the smaller particle in the reference frame of the larger particle and of course, on the materials involved.

In interplanetary space, however, even more important is the case where the kinetic energy of the collision is sufficient to fragment the larger particle completely. A discussion of the relative importance of both cases can be found in Dohnanyi (1972, Icarus, 17, 1). Catastrophic collision is more important than the slow erosion by cratering because much more mass (of the large particle) is shattered than is excavated in the cratering process. For example, at an impact speed of 10 km/s, a particle of mass m_1 can fragment a particle of mass $m_2 = 4 \times 10^5 m_1$. On the other hand, a slightly smaller projectile $m_3 = 0.5 m_1$ will only excavate a crater in a particle of mass m_2 . This ratio of the mass of the target particle m_2 to the mass of the smallest projectile m_1 which will still catastrophically destroy the larger particle depends on the square of the relative speed v .

The effects of catastrophic collisions are also important for a population of particles. If particles are all of the same size, then a collision will destroy and perhaps even vaporize both. But if there is a size distribution, e.g., $g(m) = m^{-x}$, then the most probable catastrophic collision of a given particle is with a much smaller particle because they are more numerous. The

fragments may follow a size distribution of the type $h(m)=m^{-y}$, where $y=0.83$ (Fujiwara et al., 1977). Therefore, fragmentation could change the original size distribution. Dohnanyi (1970, JGR, 75, 3468) has shown that only a distribution with a population index (x) of $11/6$ is stable against fragmentation and will not change with time. This is the case for the distribution of asteroids. If the population index is larger than $11/6$, then more particles are destroyed in a given mass interval than are generated by collisions of larger particles in the same mass interval. This is the case for large ($10^{-5}g < m < 10^2g$) interplanetary grains ($x=1.34$) which need to be replenished by a source (e.g. from comets). If the population index is smaller than $11/6$ then more particles are generated by collisions than are removed from the same mass interval. An example for this case are zodiacal particles ($10^{-10}g < m < 10^{-5}g$) which are produced mainly by fragmentation of meteor sized objects ($m > 10^{-5}g$), faster than they are destroyed by mutual collisions.

v. Search for Primitive Polycyclic Aromatic Hydrocarbons

Polycyclic Aromatic Hydrocarbon (PAH) molecules have recently been suggested as the source of IR emission bands (Leger and Puget, 1984, Astron. Astrophys., 137, L5). This identification seems to be a reasonable hypothesis but only indicates the presence of a molecular family because many members of this class of molecules can have the same IR vibrations (C-H, C-C modes). Laboratory determination of the visible spectra of PAH is being undertaken, but a great difficulty is the criterion for selection of the molecules to study (there are $>10^4$ molecules for a carbon atom number between 50 and 100). PAH molecules have been detected in meteorites (e.g. Hayatsu and Anders, 1981). If one could find such molecules in situations where there is some hope that they are primitive (in the sense of having the original chemical formula) it may be a most interesting guide to the selection of species for laboratory studies and potential spectroscopic identification.

vi. Interstellar Organic (Biogenic ?) Material

In a series of papers over the past decade, Hoyle and Wickramasinghe have argued that organic matter is the major source of interstellar opacity

(Hoyle, F. and Wickramasinghe, N. C., 1977, Nature, 268, 610). Their efforts have embraced everything from detailed fits of the wavelength dependence of interstellar extinction to theoretical arguments about the need to utilize organic compounds. If they are correct, these compounds will be the natural abundant precursors of the carbonaceous matter found in meteorites.

But there is an even more important connection between these interstellar particles and the solar system record -- life itself. Highly controversial and not accepted by most of the scientific world, they have argued that the chemical memory structures that characterize life did not originate on Earth, but were instead inherited by Earth from a larger cosmic evolution (Hoyle, F. and Wickramasinghe, N. C., 1979, Astrophys. Spa. Sci., 66, 77). They have stressed that many very deep issues are involved, even our concepts of intelligence and of the correct cosmological theory. We must at least admit that if they are correct, it is the most important connection of them all to a cosmic memory. Because of its radical nature, much of their writing has gone straight to the public (e.g. Evolution from Space, J. M. Dent and Sons, London 1981).

B. Planetary Record

Postulated relationships between the structures of planets and the structure of ISMD are much harder to pin down because the planets have been so chemically active. The question may perhaps be asked this way: "What properties of planets owe their existence to the actual structure of ISMD; i.e. What would have been different if the dust structures had been different?" Little consensus exists on these clues because they depend upon a theoretical picture of dust aggregation and modification leading to the growth of planets. Because the initial generations of dust structures are now gone, one is concerned with fine effects in the bulk composition of planets, and these fine effects are attributable to initial properties of the dust (ISMD) only with grave uncertainty at present. Studies of the transport and aggregation of dust in a model of the solar disk (e.g., Lin, 1981, Morfill and Volk, 1984, op. cit.) seem at present to offer the most likely chance of establishing a connection. But even so, an almost exactly correct description will be needed

to evaluate the small fractionation effects on the bulk compositions of planets. Planetary atmospheres could, in principle, record volatile-rich accretion over geologic time.

C. Cometary Record

Unlike meteorites, the birthdates of comets are unknown, although on good grounds they are also believed by most astronomers to have formed early in solar system history. If that is the case, comets should carry some memory of the ISM dust from which they probably formed. Although connections to ISMD then exist, the hard task in this case is the measurement of the properties of cometary material. An extensive literature exists and can be approached through Comets (University of Arizona Press: Tucson 1984). Some in situ measurements may already exist if cometary breakup is a major source of interplanetary dust particles (IDP's - see Walker's review). A returned cometary sample could become the single most informative piece of evidence of this relationship, but the proposed flybys may be almost as revealing.

Whether the comets in the Oort cloud ($d > 3 \times 10^4$ AU) were formed in-situ or were formed in the trans-Neptunian region and kicked out by the gravitational perturbations of these outer planets is still an open question. Whatever their origin, however, it is generally regarded that comets, by virtue of their small masses (leading to almost no internal heating or weathering and a negligible number of high-velocity meteoritic impacts) perhaps represent the most pristine material in the solar system. Consequently, a proper understanding of their chemical composition and physical structure (e.g. do they show a hierarchical granular structure similar to Brownlee particles) could give us important clues both to the physico-chemical environment in which they formed, as well as the basic physical processes that led to their formation. For this reason, a sample return mission to a comet in the future, following the present fly-by missions to comets Halley and Giacobini-Zinner and the proposed rendezvous mission, possibly to comet Wildt2, should be strongly supported.

1. The relationship of cometary volatiles to the ISM. The relationship of cometary volatiles to interstellar dust is unclear because it is not known whether the volatiles condensed as mantles on grains in dark clouds long before accretion into comets or condensed in the pre-solar nebula. A few points bear on the condensation process and subsequent history.

a. If S_2 is truly resident in the cometary nucleus and is not a rapidly produced daughter product, it constrains the history of the grains. In particular, it requires irradiation of sulfur compounds in grain mantles and it requires that the irradiated mantles remain very cold ($T < 30$ K) from the time of irradiation until accretion into the nucleus (A'Hearn et al. 1983, Ap. J. (Lett.), 274, L99).

b. The D/H ratio in H_2O (only upper limits exist now but better numbers will exist within 1 1/2 years) constrain the condensation process of H_2O . Condensation of H_2O on grain surfaces should lead to a temperature dependent fractionation. Since the ice band is readily observed in dark clouds, it is likely that the condensation process should take place there. Better theoretical models of the fractionation, allowing for time dependence, will be needed.

2. Cometary Refractory Grains. The large (compared to diffuse ISM) grains which are presumably friable and porous, require a very gentle aggregation process, either in clouds or in the pre-solar nebula. Do the clouds completely shield the grains from the destructive shocks of the diffuse ISM?

3. Need for In Situ Measurements. In situ experiments (e.g. from the CRAF mission) could test whether or not the C depleted from volatiles has gone into refractories by measuring the vaporization mass spectra of dust. Such a mission can, in principle, look for the isotopic anomalies found in meteorites, although getting sufficient sensitivity in flight instruments may be difficult.

II. INTERRELATIONSHIPS TODAY

A. "IDP" Captured from ISM

Because the spectrum of origins of IDP's is not known, the possibility exists that some may be captured from the ISM. Entry of ISMD into the solar system happens at all times, but especially during those epochs when the solar system passes through ISM clouds. The probability frequency of the latter is discussed in several papers in the book The Galaxy and the Solar System (University of Arizona Press: Tucson 1985). Capture in recent times would present us with particles related to ISMD today. It is still not known how large ISMD particles can be, or even if macroscopic ISMD particles exist.

1. Estimates of total accretion of interstellar grains onto Earth's Surface. Over the earth's total history, probably about a dozen clouds of density $n_H=1000 \text{ cm}^{-3}$ have been encountered. Clouds of such density will suppress the heliopause to within 1 AU of the Sun, so that the dust particles in these clouds should accrete onto the earth's atmosphere unimpeded by destruction processes associated with the solar wind. It is simplest to assume that the radiation pressure on the grain balances the Poynting-Robertson effect, a reasonable assumption for a typical a 0.1 micron particle expected for $n_H=1000 \text{ cm}^{-3}$ clouds. But see the discussion of the size distribution below.

A density enhancement of a factor of 3-10 over the ambient interstellar density is expected at 1AU for an average relative sun-cloud velocity of 20 km/s. If the earth has encountered a dozen such clouds over its history, and if each cloud encounter lasted about 10^6 years (i.e. a cloud length of 10pc), then a total integrated flux of about 0.06 g cm^{-2} is expected on the earth's surface, or a total accumulation of 9×10^{20} grams. At an average grain density of 3 g/cm^3 , this is enough to build about 25 mountains the size of Mount Everest. This interstellar component is unfortunately swamped by the much larger influx of solar system micrometeorites (Barker and Anders, 1968, Geochim. Cosmochim. Acta, 32, 175).

2. Interstellar "IDP" Effects on Lunar Soils. At the present time the solar system is apparently located in a region of space that is not densely populated with interstellar gas and dust. However, this has almost certainly not been true for its entire history. At various times in the past, the solar system must have encountered dense, interstellar gas/dust clouds (see The Galaxy and the Solar System (Tucson 1985)). In principle, the record of such encounters could be preserved in individual crystals of the lunar regolith. Individual lunar soil grains have typically been exposed for 10^4 years at the very surface of the moon. Crystals removed from different depths and from different cores were exposed at various times in the past - in some cases at least 10^9 years ago. The record of surface exposure is manifested by the presence of micrometeoritic impact craters, solar wind implanted ions, and solar flare tracks. Passage through a dense dust cloud would produce crystals with a higher average density of impact pits relative to implanted solar wind ions than crystals exposed at the lower surface. Initial attempts to look for an effect were defeated by the presence of glass splashes on grain surfaces which masked the Mg contribution which was being used as a tracer of implanted solar wind. Recent advances in instrumentation have made it possible to re-examine this question using nitrogen as the solar wind tracer. Since the indigenous nitrogen concentration is low on the moon, its use as a tracer of solar wind exposure should not be compromised by the presence of glass splashes. While admittedly an extremely difficult experimental problem, it is still worthwhile to attempt to use lunar samples to establish a fuller record of the history of the solar system than has thus far been done. Again, however, it is necessary to separate the interstellar component from a much greater influx of more mundane solar system particles (see Anders et al., 1973, The Moon, 8, 3).

3. Dynamical Aspects of Today's Intersellar/Interplanetary Connection. Interplanetary matter contributes to the interstellar medium via the injection of small particles ($m < 10^{-12}$ g) into hyperbolic trajectories under the influence of radiation pressure. There are two processes which generate these small particles: (1) evaporation of comets in the inner solar system with the subsequent release of cometary dust, and (2) collisional fragmentation of larger interplanetary meteoroids. The outflux of both types of particles from the

solar system is of the order of 10 tons per second (Delsemme 1976, Lecture Notes in Physics, 48, 314; and Grün et al, 1985, Icarus in press).

On the other hand, interstellar grains will enter the solar system and may be observable there. There are certain dynamical processes which affect the trajectories and which lead to a dispersion of incoming interstellar grains. Radiation pressure reduces the gravitational attraction by the sun. The parameter which quantifies this effect is the ratio of the radiation pressure force F_{rad} over the solar gravitational force F_{grav} : $\beta = F_{\text{rad}}/F_{\text{grav}}$. This ratio is a function only of particle parameters such as the size (s), density (ρ) and optical scattering efficiency Q : $\beta = Q/sp$. For micron- and submicron-sized particles β reaches unity and may even exceed it. For smaller particles, it decreases (pure dielectric materials) or stays close to unity (absorbing materials). The effect of $\beta > 1$ for small particles is that they are repelled from the sun rather than being attracted by it. The result will be that these small particles reach only a minimum distance from the sun which depends on their incoming velocity.

Another effect is due to the interaction of interstellar grains with the solar wind. Solar wind ions impinging on dust particles also exert a repelling force on the grains which, for submicron-sized dielectric particles, may become the dominating force. Therefore, very small (< 0.1 micron) dielectric particles are shielded from the inner solar system.

A third effect which acts to prevent small interstellar grains from reaching the inner solar system is the electromagnetic interaction between charged dust particles and the interplanetary magnetic field. Dust particles within the heliosphere will be charged positively because of the prevailing photoelectric effect, which exceeds the charging by solar wind electrons. The surface potential is estimated to be of the order of 10V independent of the solar distance (Rhee, 1969). The charged interstellar dust grains interact with the interplanetary magnetic field. For micron sized particles this force is only a small perturbation compared to the force exerted by gravity and radiation pressure. For 0.1 micron sized particles however, the electromagnetic force is comparable to the others. Morfill and Grün (1979, Planet.

Space Sci.) have shown that interstellar grains may be focused towards or dispersed away from the current sheet located close to the ecliptic plane, depending on the configuration of the overall solar magnetic field which varies with the solar cycle. Small charged particles entering the solar system at high solar latitudes will encounter only a unipolar field which will effectively repel them all the time.

The upshot of these considerations is that submicron-sized (<0.1 micron) particles made from either absorbing (carbon or metal rich) or dielectric (silicates) material will not reach the inner solar system. Their closest approach depends on their speed with respect to the Sun and on their exact composition (pure dielectrics may get somewhat closer). However, particles larger than a micron are not repelled by the effects discussed above and may even be gravitationally concentrated in the solar system just as the interstellar wind is (Fahr (1974) Space Sci. Rev., 15, 483). Therefore, a crucial prerequisite for the capture of interstellar grains near 1AU is the existence of sufficiently large particles in the ISM. From in-situ interplanetary dust measurements (see interplanetary grain report) there are indications that some of the recorded particles may have an interstellar origin.

4. Alteration of SSD on Parent Bodies. Fortunately many minerals in chondritic IDP's may retain identifiable memory regarding previous events such as processes that affected the IDP's after accumulation and residence in a protoplanetary parent body (Rietmeijer, 1985-a; -b; see also Sandford and Walker, 1985 Ap. J., 291, 838), during their solar system sojourn and atmospheric entry. Prominent among these minerals are Epsilon (E-) carbide, poorly graphitized carbon, layer silicates and Bi_2O_3 . The E-carbide (Christoffersen and Buseck, 1983) is of interest because it may be a residue of Fischer-Tropsch reactions which have been proposed by Anders and coworkers as a possible source of solar-system hydrocarbons (cf. Studier et al., 1972).

Rietmeijer and Mackinnon (1985-a) suggested that catalytically activated hydrous pyrolysis below about 300°C may affect "hydrocarbon compounds" in chondritic IDP's to produce amorphous carbon. Continued heat-treatment at temperatures below about 500°C induces graphitization resulting in the forma-

tion of poorly graphitized carbon (PGC) similar to PGC in carbonaceous chondrites (Rietmeijer and Mackinnon, 1985-b). The degree of graphitization is a potential cosmo-thermometer for primitive extraterrestrial materials (Rietmeijer and Mackinnon, 1985-b).

The debate on the origin of layer silicates in primitive extraterrestrial materials (carbonaceous chondrites) centers on the question of whether they are the result of low-temperature aqueous alteration (McSween et al., 1979; Bunch and Chang, 1980) or whether they have formed by direct vapor phase condensation (Lewis, 1972; Saxena and Eriksson, 1983). In general, layer silicates are common alteration products of anhydrous silicates. Recently it has been suggested that the alteration processes may take place at room temperature (25°C) or even below the melting point of water ice (Gooding, 1984; Rietmeijer and Mackinnon, 1984-a; Rietmeijer, 1985-a, -b).

Layer silicates have been observed in five IDP's -- IDP XP-36 (Brownlee, 1978); LOW-CA, a hydrated IDP; Skywalker and Calrissian (Tomeoka and Buseck, 1984; 1985-a; -b) and in CPA W7029*A (Mackinnon and Rietmeijer, 1983; Rietmeijer and Mackinnon, 1984-b, 1985-c). The most abundant layer silicate in IDP's is a smectite, or a mica of similar composition. A phase which may be comparable with the IDP layer silicate has been described from a fine-grained CAI in the Allende (CV) meteorite (Tomeoka and Buseck, 1982). Other, less abundant, groups of layer silicates in IDP's are chamosite or serpentine (Brownlee, 1978), a poorly crystalline Fe-rich layer silicate (Tomeoka and Buseck, 1985-a, -b; Rietmeijer and Mackinnon, 1984-b, 1985-c), Mg-poor talc and kaolinite (an Al-rich layer silicate) (Mackinnon and Rietmeijer, 1983; Rietmeijer and Mackinnon, 1985-c). Layer silicates in these IDP's are not similar to the predominant layer silicates in CM chondrite matrices and are also probably dissimilar to layer silicates in CI chondrites, although detailed Analytical Electron Microscope analyses on CI meteorites are not available (Rietmeijer and Mackinnon 1985).

Although the diversity of layer silicates in IDP's probably points to low-temperature alteration of IDP's in a proto-planetary parent body, the large stability fields of the IDP layer silicates render them generally un-

suitable to more precisely constrain the alteration process. One noticeable exception is kaolinite, the presence of which in IDP's suggests that (1) during solar system transit heating of the IDP was minimal and (2) low water vapor pressures may have prevailed in the IDP (Rietmeijer and Mackinnon, 1985).

In Chondritic Porous Aggregate (CPA) W7029*A single crystals of Bi_2O_3 formed via oxidation of Bi-metal in response to flash-heating of this aggregate during its atmospheric entry. The simple cubic structure of this oxide indicates that this mineral formed below about 300°C (Mackinnon and Rietmeijer, 1984). This low entry temperature agrees well with the preservation of nuclear tracks in olivines found in IDP's [Bradley et al., 1984].

In general, a careful study of the mineralogy of IDP's may reveal detailed pieces of its memory, which may eventually enable us to isolate unaltered ISM dust grains in chondritic IDP's and even in primitive meteorites.

5. Searching for relatively Unaltered Material. The look we get at the properties of presolar material through the study of meteoritic material is clouded and obscured by the event of solar system formation which obliterated much of the information we seek. Although continued study of the meteoritic record will increase our knowledge of presolar material, it is imperative to concentrate on material which is primordial, i.e. which has not been effected by the solar system formation event. This includes:

a) Intensified work on interplanetary dust particles collected in the stratosphere (IDPs). Judged by the percentage of IDPs exhibiting D-excesses, these particles as a class of material are more primitive than primitive meteorites.

b) Collection of interplanetary dust particles from known sources. Orbital parameter determination in conjunction with collection of material in space would enable us to distinguish between grains of cometary and asteroidal origin as well as (hopefully) present day interstellar grains. Experiments of this type have been proposed for implementation on the Space Station.

- c) Collection of cometary material during a fly-by mission.
- d) Collection of material during a comet sample return mission (solid material and gas).
- e) Possible future missions dedicated to the collection of dust and ice from the rings of the outer planets.

All experiments designed to trap and analyze the atoms from impacting interplanetary dust particles are currently orbiting the earth on the Long Duration Exposure Facility (LDEF I). The spacecraft is due to be returned to earth at the end of the Summer 1986. Both elemental and isotopic measurements (with a precision of 1/1000) will be made. One interesting question to be answered is the extent to which particles collected in this way will show similar isotopic effects to those that have already been measured in IDPs collected in the upper atmosphere (Walker, this workshop). A sneak-preview of the LDEF I experiments is provided by the return of parts from the Solar Maximum Satellite which show impacts from chondritic and iron-sulfide micro-meteoroids (Schramm et al., 1985, LPSC XVI, 736).

The current experiments are only crude precursors to what could be flown to identify, collect, and analyze cosmic dust from known sources. With a reasonable extrapolation of existing technology, it appears feasible to measure the time of arrival of individual particles and, more important, to determine their velocities i.e.: the orbital parameters of particles whose isotopic composition could be measured. An array of many individual "active" capture cells - those that would measure the location, velocity, and time-of-arrival has been proposed as a potential space station experiment (see Bank's report on the scientific uses of the space station; also Zinner and Walker, this conference). Individual cells containing impacts with "interesting" orbital parameters could be removed periodically from the large array and returned to earth for detailed study.

Interesting orbits would be those which indicated that the particles originated either from specific comets or came directly from the interstellar

medium, that is, those particles whose orbits were out of the plane of the ecliptic and/or whose velocities were equal to or greater than the escape velocity of the solar system.

Although it is only conjectural at this point, comets appear to be a promising place to look for primordial solar system matter (NAS report on small bodies) and interstellar dust that escaped drastic modification during the formation of the solar system.

With existing laboratory instrumentation, it is possible to obtain precise isotopic measurements on impacts from 10 micron particles. The flux of interstellar particles of this size traversing the solar system cannot be calculated exactly from current knowledge, but it is certainly low. If such particles could be captured and studied it would open up a new chapter in experimental astrophysics. However, even if only interplanetary particles were measured, the experiment, which has been given the acronym ODACE (Orbital Determination and Capture Experiment), (Walker and Zinner, this conference), would contribute important new knowledge about primitive materials.

B. IDPs Stored in Regoliths

If solid bodies have accreted ISM dust during solar system history, IDPs liberated during collisions with those bodies may be directly related to ISMD. This rather remote connection of current IDPs to the ISM will be very hard to establish even if it exists.

C. Circumstellar Material Around Other Stars

An entirely new perspective on the relationship between interplanetary and interstellar material may arise from studies of the solid material orbiting other stars, first recognized in IRAS data and recently confirmed with optical observations. This field of investigation is sufficiently new and difficult observationally that the level of detailed characterization of the material which will eventually be attained is difficult to project. However, these new samples of material which have survived the transition from the

interstellar medium to long-lived near-stellar disks, should, by virtue both of their similarities to and differences from solar system material, provide new clues to the character of the primordial material and the changes inherent in this material resulting from stellar formation.

ADDITIONAL REFERENCES

Bradley, J. P., Brownlee, D. E. and Fraundorf, P., Discovery of nuclear tracks in interplanetary dust, Science, 226, 1432-1434, 1984.

Brownlee, D. E., Interplanetary dust: Possible implications for comets and presolar interstellar grains, In Protostars and Planets (ed. T. Gehrels) (Univ. of Arizona Press, Tucson, 1978) pp. 134-150.

Brownlee, D. E., Rajan, R. S. and Tomandl, D. A., A chemical and textural comparison between carbonaceous chondrites and interplanetary dust, In Comets, asteroids, meteorites interrelations, evolution and origins (ed. A. H. Delseemme), (Univ. Toledo, Toledo, 1977) pp. 137-141.

Bunch, T. E. and Chang, S., Carbonaceous chondrites-II. Carbonaceous chondrite phyllosilicates and light element geochemistry as indicators of parent body processes and surface conditions, Geochim. Cosmochim. Acta, 44, 1543-1577, 1980.

Christoffersen, R. and Buseck, P. R., Epsilon carbide: A low-temperature component of interplanetary dust particles, Science, 222, 1327-1329, 1983.

Fraundorf, P., Interplanetary dust in the transmission electron microscope: diverse materials from the early solar system, Geochim. Cosmochim. Acta, 45, 915-943, 1981.

- Fraundorf, P., Brownlee, D. E. and Walker, R. M., Laboratory studies of interplanetary dust, In Comets (ed. L. L. Wilkening) (Univ. Arizona Press, Tucson, 1982) pp. 383-409.
- Gooding, J. L., Aqueous alteration on meteorite parent bodies: possible role of "unfrozen" water and the Antarctic meteorite analog, Meteoritics, 19, 228-229, 1984.
- Hayatsu, R. and Anders, E., Organic Molecules in Meteorites and their Origins, Topics in Current Chemistry, 99, 1-37, 1981.
- Lewis, J. S., Metal/silicate fractionation in the solar system, Earth Planet. Sci. Lett., 15, 286-290, 1972.
- Mackinnon, I. D. R., McKay, D. S., Nace, G. A. and Isaacs, A. M., Classification of the Johnson Space Center Stratospheric Dust Collection, Jour. Geophys. Res., 87, Supl., A413-A421, 1982.
- Mackinnon, I. D. R. and Rietmeijer, F. J. M., Layer silicates and a bismuth phase in chondritic aggregate W7029*A, Meteoritics, 18, 343-344, 1983.
- Mackinnon, I. D. R. and Rietmeijer, F. J. M., Bismuth in interplanetary dust, Nature, 311, 135-138, 1984.
- McKay, D. S., Rietmeijer, F. J. M. and Mackinnon, I. D. R., Mineralogy of chondritic porous aggregates: Current status, In Lunar and Planetary Science XVI, (Lunar and Planetary Institute, Houston, 1985) pp. 536-537.
- McSween, Jr., H. Y., Are carbonaceous chondrites primitive or processed? A review, Rev. Geophys. Space Phys., 17, 1059-1078, 1979.
- Rietmeijer, F. J. M., On the continuum between chondritic interplanetary dust and CI and CM carbonaceous chondrites: A petrological approach, In Lunar and Planetary Science XVI, (Lunar and Planetary Institute, Houston, 1985) pp. 698-699.

Rietmeijer, F. J. M., A model for diagenesis in proto-planetary bodies, Nature, 313, 293-294, 1985-a.

Rietmeijer, F. J. M., Low-temperature aqueous and hydrothermal activity in a proto-planetary body: Goethite, opal-CT, gibbsite and anatase in chondritic porous aggregate W7029*A, In Lunar and Planetary Science XVI, (Lunar and Planetary Institute, Houston, 1985-b) pp. 696-697.

Rietmeijer, F. J. M. and Mackinnon, I. D. R., Diagenesis in interplanetary dust: chondritic porous aggregate W7029*A, Meteoritics, 19, 301, 1984-a.

Rietmeijer, F. J. M. and Mackinnon, I. D. R., Layered silicates in chondritic porous aggregate W7029*A: A case of primary growth, In Lunar and Planetary Science XV, (Lunar and Planetary Institute, Houston, 1984-b) pp. 687-688.

Rietmeijer, F. J. M. and Mackinnon, I. D. R., A multi-stage history for carbonaceous material in extraterrestrial chondritic porous aggregate W7029*A and a new cosmo thermometer, In Lunar and Planetary Science XVI, (Lunar and Planetary Institute, Houston, 1985-a) pp. 700-701.

Rietmeijer, F. J. M. and Mackinnon, I. D. R., A new cosmo thermometer for primitive extraterrestrial materials: Poorly graphitized carbon, Nature, in the press, 1985-b.

Rietmeijer, F. J. M. and Mackinnon, I. D. R., Layer silicates in primitive extraterrestrial materials: Chondritic porous aggregate W7029*A, Jour. Geophys. Res., in the press, 1985-c.

Saxena, S. K. and Eriksson, G., Low- to medium-temperature phase equilibria in a gas of solar composition, Earth Planet. Sci. Lett., 65, 7-16, 1983.

Studier, M. H. Hayatsu, R. and Anders, E., Origin of organic matter in early solar system-V. Further studies of meteoritic hydrocarbons and a discussion of their origin, Geochim. Cosmochim Acta, 36, 189-215, 1972.

Tomeoka, K. and Buseck, P. R., Intergrown mica and montmorillonite in the Allende carbonaceous chondrite, Nature, 299, 326-327, 1982.

Wilkening, L. L., Carbonaceous chondritic material in the solar system, Naturwissenschaften, 65, 73-79, 1978.

Zinner, E., McKeegan, K. D. and Walker, R. M., Laboratory measurements of D/H ratios in interplanetary dust, Nature, 305, 119-121, 1983.