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STAR FORMATION AND THE SOLAR SYSTEM*

John Bally
AT&T Bell Laboratories

Alan Boss
Dept. of Terrestrial Magnetism
Carnegie Institution of Washington

Dimitri Papanastassiou
Dept. of Geology
California Institute of Technology

Scott Sandford
NASA/Ames

Anneila Sargent
Dept. of Physics
California Institute of Technology

The Solar System provides a unique fossil record of a single star formation event. Investigation of a variety of materials such as interplanetary dust, meteorites, and comets may provide us with information about physical processes which operate on scales totally inaccessible to study in observable star forming regions. However, our increasing ability to probe on-going star formation regions on sub-arc-second scales allows us to gather information about cosmogonic events on large scales. This paper investigates the overlap between the study of other star-forming regions and the Solar System.

1. INTRODUCTION

The last several decades have witnessed a remarkable series of developments which have revolutionized our thinking about the formation of stars and planetary systems. The opening of most of the electromagnetic spectrum between radio and optical wavelengths led to the recognition that stars form from cold, dusty molecular clouds. The frequent occurrence of violent activity in association with star formation has been demonstrated by

* This paper represents a synopsis of a panel discussion held at Whistler on Wednesday evening, June 24, ,1987.

the discovery of bipolar outflows, jets, and hot shock excited gas in the circumstellar environment of recently formed stars. Despite a multitude of impressive gains, observations of on-going star formation are inherently limited to scales larger than about 10^{14} cm (corresponding to 0.1" at a distance of 100 pc). The jets, outflows and disks observed so far have dimensions ranging from 10^{15} to over 10^{17} cm (10^{2} to 10^{4} A.U.). However, most important physical processes associated with star formation such as accretion, flow acceleration and collimation, and formation of compact bodies such as planets and the parent star itself occur on scales smaller than this.

Study of the "fossil" record left from the formation of the Solar System provides an opportunity to learn about processes occurring on the small scale. Investigation of meteorites and interplanetary dust particles gathered from the upper atmosphere has provided a glimpse of some of the physical processes and conditions prevailing during the star formation event which gave birth to the Solar System. Figure 1 is a schematic plot of the size scales and characteristic distances from a proto-star at which various objects familiar to us can be found. Also illustrated are the regions accessible to observation in the nearest star forming regions.

A complete picture of star and planet formation requires a synthesis between the results of studies carried out by observation of active star forming regions and the results of analyses of Solar System materials. There are many phenomena which have yet to be fit into a "unified" theory of star formation. How do powerful winds and outflows effect the development of the proto-planetary disk? How do comets form? What are the physical conditions in this disk? What is its evolutionary history? Table 1 is a partial list of some of the questions which must be answered before we can truly claim to have understood the formation of the Solar System and of stars.

The continued collaboration between "astronomers" and "planetologists" will be required to address many of these issues. This panel discussion was organized to focus on the need for such collaboration. This paper, based on presentations made during the panel discussion by the co-authors, reviews several aspects of ongoing studies of star-formation and Solar System material. We concentrate on studies which provide information on the physical conditions (temperature, densities, compositional mixing, etc.) in the Solar Nebula. These studies include (1) studies of gas in nearly circumstellar disks (reviewed by A. Sargent), (2) History, and survival of grains as they are incorporated from the ISM into the Solar System (reviewed by A. Boss), (3) Physical conditions in the Solar Nebula deduced from studies of interplanetary dust particles (IDP's) (reviewed by Scott Sandford), and (4) Isotopic anomalies in Solar System materials (reviewed by D. Papanastassiou).

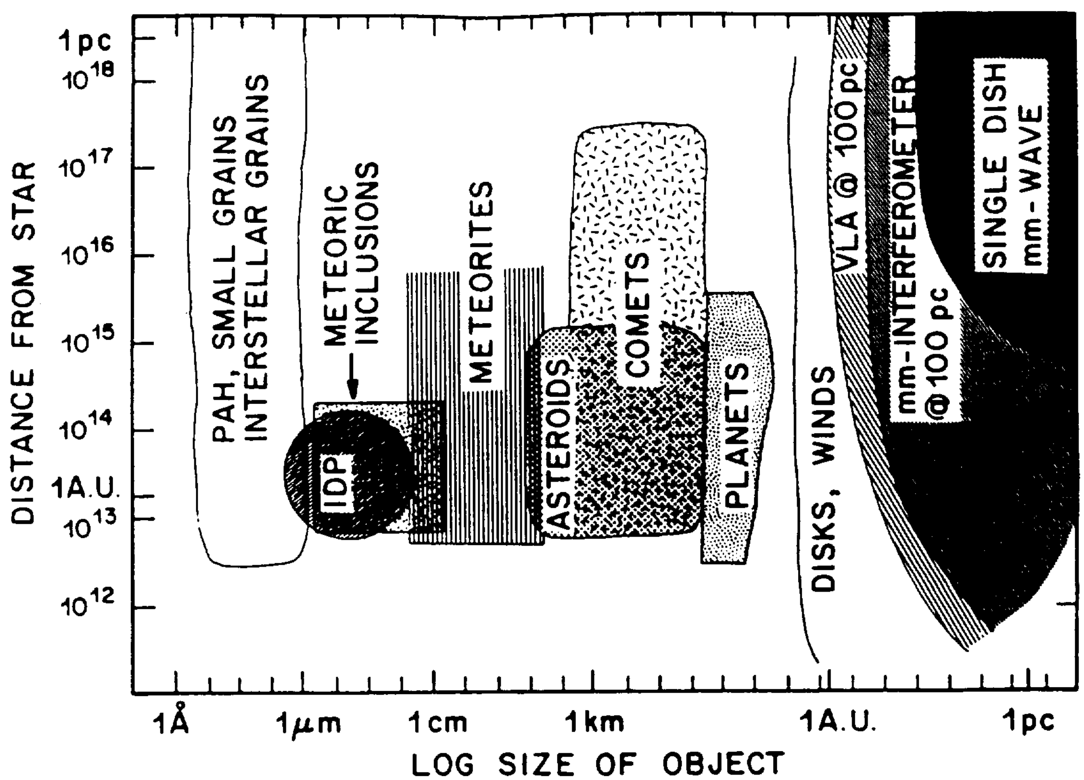

Figure 1 Schematic plot showing the size and distance domains occupied by a variety of familiar objects in the Solar System environment. The right hand side of the figure illustrates the region of this parameter space which can be accessed by a variety of ground based observational methods.

TABLE 1

SOME QUESTIONS ABOUT STAR FORMATION AND THE ORIGIN OF THE SOLAR SYSTEM

- What were the physical conditions in the Solar Nebula?
    - What was the density and temperature structure? Did B fields play a role? Mixing; was nebula homogeneous or lumpy? What are the time scales for the formation of various structures?
- What are the most "primitive" Solar System samples?
    - What "pre-solar" materials can be identified?

    - What species can be detected in ISM and in Solar System? D/H ratio, C, N, O, S, ... etc. isotopes, PAH's?
    - Are "live" nucleosynthetic products incorporated from ISM or formed in-situ by energetic processes?
    - Is there evidence for a Solar T-Tauri phase?
    - How complex are primitive organics? Where and how do they form?
- How did comets form? Do they provide a record of the most "primitive" material?
- How do larger bodies (meteoroids, asteroids, planets, etc.) accumulate?
- How frequently do planetary systems form?

2. GAS IN DISKS SURROUNDING YOUNG STARS

Stars are born in the densest parts of the clouds of gas and dust which populate interstellar space, and observations show that remnants of these clouds remain associated with young objects for a substantial period. On theoretical grounds, it is expected that this circumstellar material will be distributed in flattened, disk-like structures.

As long ago as 1796, Laplace proposed that our Solar System planets originated from just such a large gaseous disk, surrounding a very young Sun. While the details of the hypothesis have been heavily modified with time, modern cosmogony still relies on the existence of this disk phase in the evolution of young stars to explain the origin of the planets. It is therefore clear that our knowledge of the mechanisms involved in star formation profoundly affects our understanding of the way in which the Solar System was created.

Studies of proto-stellar evolution were, until very recently, hampered by the fact that young objects are frequently still obscured by remnants of their parent clouds and are thus undetectable at visible wavelengths. However, with the advent of infrared and millimeter wavelength observations, investigations of the properties of the material around proto-stars and pre-main-sequence objects have become feasible. Indeed, technological innovations over the last five years — the Einstein, IUE, and IRAS satellites (operating at X-ray, ultra-violet and infrared wavelengths respectively), as well as near-infrared speckle and millimeter wave interferometry from ground-based sites — have made it possible to examine regions of star formation in unprecedented detail. In fact, the few hundred AU scales required to detect proto-planetary systems have become accessible.

Regions where relatively low mass stars are forming are perhaps the best sources of information on early stellar evolution. Since lower mass stars spend longer times on their pre-main-sequence tracks than do their higher mass counterparts, and since they are likely to have a considerably less disruptive effect on their immediate environments, their various stages of development are more easily accessible to observations. Often, in such regions, young stellar objects are already visible as T-Tauri stars which are very young ($\leq$ a few $\times 10^6$ years), solar-type (spectral class G, K, or M) variables, with masses in the range 1 to 3 $M_\odot$. Their infrared colors suggest the presence of significant amounts of circumstellar dust, and their spectra show P Cygni profiles indicating mass-loss; some are also the source of high-velocity molecular outflows. Since it is generally supposed that the Sun experienced a T-Tauri phase in its pre-main-sequence evolution, observations of members of this class are vital to understand the origins of our Solar System.

To this end, a wide variety of studies, exploiting all the advantages of the new technologies, have been undertaken. For example, X-ray and ultraviolet observations have shown that the atmospheres of many T-Tauri stars can be described by a two component model, very similar to that which applies to the Sun. In addition, the detection of enhanced ultraviolet and X-ray fluxes relative to those of the present-day Sun have suggested a means of explaining the abundance anomalies now seen in the Solar System; it is possible that violent flare activity and high proton fluxes produced the unusual chemical conditions in the pre-Solar Nebula, and affected the atmospheres of the forming planets.

The IRAS satellite observations have proven to be valuable in examining the stages of stellar evolution when proto-planetary disks may still be present. The observed infrared excesses imply the existence of circumstellar disks of dust having dimensions and masses similar to the early Solar Nebula around α Lyrae, ϵ Eridani, and β Pictoris, as well as a number of other main-sequence stars. These are relatively old objects, with ages around 10^8 years; these disks may be in an advanced stage of evolution. It has been suggested that the material surrounding α Lyr and β Pic is already in particulate form and moving in coplanar orbits.

More recently, near-infrared speckle interferometry, and maximum entropy reconstruction of near-infrared images, have provided access to an even earlier phase of planetary formation (Beckwith *et al.* 1984, Grasdalen *et al.* 1984). Very high resolution ($\leq 0.5''$) measurements of scattered light demonstrate that a few pre-main-sequence stars are surrounded by asymmetric envelopes of dust. Like the IRAS 'disks', the derived masses and sizes are similar to those of the pre-planetary Solar Nebula.

However, in spite of all these tantalizing findings, there is still very little real evidence that a forming Solar System has been detected. The IRAS data suggests that as many as one in five stars may support planetary systems, but the indications of planetary formation are limited; and, while the morphologies derived from speckle and maximum entropy techniques are very suggestive, these dust measurements provide no dynamical information and only lower limits to the total mass of gas and dust around the pre-main-sequence stars. It is clear that, in the future, observations which unambiguously define Solar Systems in-the-making will be of critical importance.

Thus, further investigations of T-Tauri stars and possible post T-Tauri stars with both the Space Telescope and the proposed X-ray satellite, AXAF, might be expected to yield information about the evolution of the ultraviolet and X-ray properties of solar-type stars. This, in turn, should constrain both the initial and expected abundance ratios in the Solar System. Ground-based, optical, coronagraph measurements of β Pictoris have already demonstrated that the material whose presence is implied by the IRAS fluxes is distributed in a highly flattened disk. If the constituent particles are moving around the star, their orbits must be coplanar with this disk, suggesting a relatively early stage of planetary formation. The size of the disk, about 400 AU, is much larger than that of the current Solar System but not unexpected for the pre-planetary Solar Nebula. Similar measurements, especially from space, of other potential planetary systems identified by the IRAS survey will make it possible to determine the spatial distribution of the circumstellar material.

For pre-main-sequence stars, where the circumstellar material is still relatively concentrated, millimeter wave interferometry will provide considerable structural and dynamical information. For example, Owens Valley Radio Observatory aperture-synthesis mapping at 2.7 mm around the T-Tauri star, HL Tauri, has shown that the circumstellar gas is distributed in a flattened, disk-like structure, 2000 AU in radius, having a mass of $\approx 0.1\ M_{\odot}$. Unlike dust continuum measures, these spectral line observations allow an analysis of the velocity structure, and show that the material is moving about the star in Keplerian orbits, as might be expected in the very early stages of a forming Solar System. The dynamical behavior of the gas is consistent with the central object being of approximately solar mass; the position of HL Tau on evolutionary tracks suggests a mass of $1\ M_{\odot}$. An interferometer survey of other T-Tauri stars should clarify the morphology and dynamics of the material around these very young stars and establish how frequently Keplerian rotation is observed. In addition, high resolution continuum mapping at 2.7 and 1 mm will provide much-needed spectral data and allow an assessment of the particle size distribution. A knowledge of both properties is critical to identifying potential planetary systems.

With currently available instrumentation, searches for Solar Systems like our own must be largely confined to relatively nearby star-forming clouds, principally because of resolution requirements. Obviously, the scope will be considerably widened as space facilities such as AXAF, ISO, SIRTF, and LDR come into service. It is also clear that millimeter and sub-millimeter interferometry from space, if successful, could provide a wealth of data concerning both the physical and chemical environments around forming stars and hence about the origins of our Solar System.

3. SURVIVAL OF INTERSTELLAR GRAINS

In this section we consider whether or not it is theoretically likely that relict interstellar grains may be found in Solar System bodies such as asteroids, comets, meteorites, and interplanetary dust particles. Following their initial condensation in the cool envelopes of stars such as supernovae, novae, and red giants, interstellar dust grains are ejected by stellar winds and deposited in the interstellar medium. Relict interstellar grains must then be able to survive four distinct phases of evolution: existence in interstellar clouds, proto-stellar collapse and passage into the Solar Nebula, existence in the Solar Nebula prior to accumulation into planetary bodies, and the accumulation process itself.

The abundance and physical nature of interstellar dust is important in considerations of star and planetary system formation since solids (i) modify the behavior and the composition of interstellar gases through grain-gas interactions, (ii) mediate lots of interesting chemistry, and (iii) are probably responsible for the transport of many (if not most) of the materials that ultimately end up in planetary systems. In dense molecular clouds where the grain temperature is low (10-30K), gas molecules will freeze out onto solid dust grains. These molecules are then lost to the interstellar gas component until they are released by grain-grain collisions, photolytic desorption, etc. A great deal of evidence exists supporting the presence of ice mantles on interstellar grains in dense, cold clouds (cf. Tielens, *et al.*, 1984). These ices are known to contain H_2O and CO, and probably also contain simple alcohols, ammonia, and all the other molecules that are typically seen in the gas phase in dense molecular clouds. The simple molecules in these ices can be modified while in the solid state through interaction with UV photons and cosmic rays resulting in the production of complicated chemical components that could not have been easily formed (or formed at all) in the gas phase. Reactions catalyzed on grain surfaces will also modify the chemical composition of these materials. Examples of such alteration processes are discussed by Tielens and Hagen (1982) and d'Hendecourt *et al.*, (1985). Some of the more volatile of these components may be returned to the interstellar gas phase, while the more refractory material probably remains with the silicate or carbonaceous core. Careful observations of the ice absorption bands in the infrared spectra of many condensed objects can potentially provide a great deal of information about the thermal and radiation history of the grains (cf. Sandford *et al.*, 1987).

Interstellar grains in diffuse clouds ($n \approx 10$ H cm^{-3}) have sizes ranging from 0.001 to 0.1 μ, with the average size being about a factor of two larger in dense clouds ($n \approx 10^4$ H cm^{-3}). Dust grains composed primarily of elements heavier than hydrogen and helium account for about 1–2% of the mass of the interstellar medium.

Dust grains can be destroyed by a number of processes (Shull 1977; Scalo 1977). Collisions between grains and hydrogen and helium ions or atoms (sputtering) are effective in stripping elements off grains provided the impact velocity is sufficiently high. Relative velocities (v_r) of 20 to 50 km s^{-1} are sufficient to remove icy species such as CH_4, NH_3, and H_2O, while $v_r \approx$ 150—200 km s^{-1} is needed to strip refractory silicates (Si and metal oxides) from grains. Relative velocities of this size can occur in the strong shock waves produced by energetic stellar winds interacting with circumstellar material. Collisions between grains can result in shattering of the grains at $v_r \approx$ 1 km s^{-1}. Collisions at $v_r \approx$ 3 km s^{-1} can evaporate icy grains, and collisions at $v_r \approx$ 8 km s^{-1} can evaporate silicate grains. However, collisions between grains are infrequent because the number density of grains is small ($n_{grains}/n_H \approx 10^{-11}$). Other processes which can destroy grains are photodesorption by UV light, sublimation, and cosmic ray sputtering.

Draine and Salpeter (1979) have considered all of these destructive processes and estimate the following lifetimes for individual grains in quiescent interstellar clouds: $\approx 2 \times 10^6$ years for pure CH_4 grains, and $\approx 5 \times 10^7$ years for pure H_2O grains. For icy grains which have been subjected to supernovae shocks, where v_r is large enough to produce efficient sputtering, the lifetimes are decreased by a factor of about 10. Silicate grains subjected to supernovae shocks have mean lifetimes of about 10^8 years, but silicate grains in quiescent, dense clouds are much longer lived. The estimated lifetimes for shocked icy grains are comparable to the ages of dense (small) interstellar clouds, but less than the ages of diffuse clouds and giant molecular clouds, so that icy grains are likely to be destroyed in clouds with supernovae and energetic stellar winds. Silicate grains, however, can survive even the most destructive interstellar cloud environments.

Even if individual grains are destroyed, this does not mean that the whole grain population is depleted, because grain growth mechanisms must also be considered. Two processes are important: accretion of gas phase species and coagulation following collisions at low v_r. The time scale for gas accretion by grains is comparable to the free fall time of a cloud with $n \approx 10^4$ H cm^{-3} (Burke and Silk 1976; Scalo 1977). Because the free fall time is a lower bound on the age of a cloud, this means that gas accretion is rapid. Thus icy grains may be reworked by sputtering and subsequent gas accretion, but never completely destroyed in interstellar clouds.

Coagulation requires a means of generating gentle relative velocities between grains. Turbulence and Brownian motion are the preferred means (e.g., Scalo 1977). Even for turbulence and Brownian motion, however, the time scales for growth by coagulation are about 10 and 10^4 times the free fall time, respectively, so that only modest growth can be expected in interstellar clouds. The process of grain coagulation only becomes significant at the much higher densities encountered in collapsed interstellar clouds, i.e., proto-stellar disks.

The dense interstellar cloud which underwent gravitational collapse to form our Solar System apparently started from a slowly rotating state (e.g., Boss 1985), which allowed the lowest angular momentum material to fall onto a central core that became the proto-sun, surrounded by a flattened disk of matter with higher angular momentum. Subsequent gas and dust infalling onto the Solar Nebula then must have passed through the radiation field of the growing proto-sun, and the accretion shock separating the surface of the nebula from the infalling cloud envelope.

Figure 2 shows the expected temperature of gas and dust heated by the radiation from a 1 $M_\odot$ protostar accreting mass at a rate of $10^{-5}\ M_\odot$ year^{-1} (Adams and Shu 1985). This calculation ignores the effects of rotation and so overestimates the temperatures encountered by grains falling onto the Solar Nebula instead of the central proto-sun. Icy grains, which evaporate at temperatures of $\approx 100 - 200$ K, may only survive outside of ≈ 50 AU, unless they are shielded from the proto-sun by the flattened Solar Nebula, but refactory silicate grains will survive to within distances of at least 1 AU.

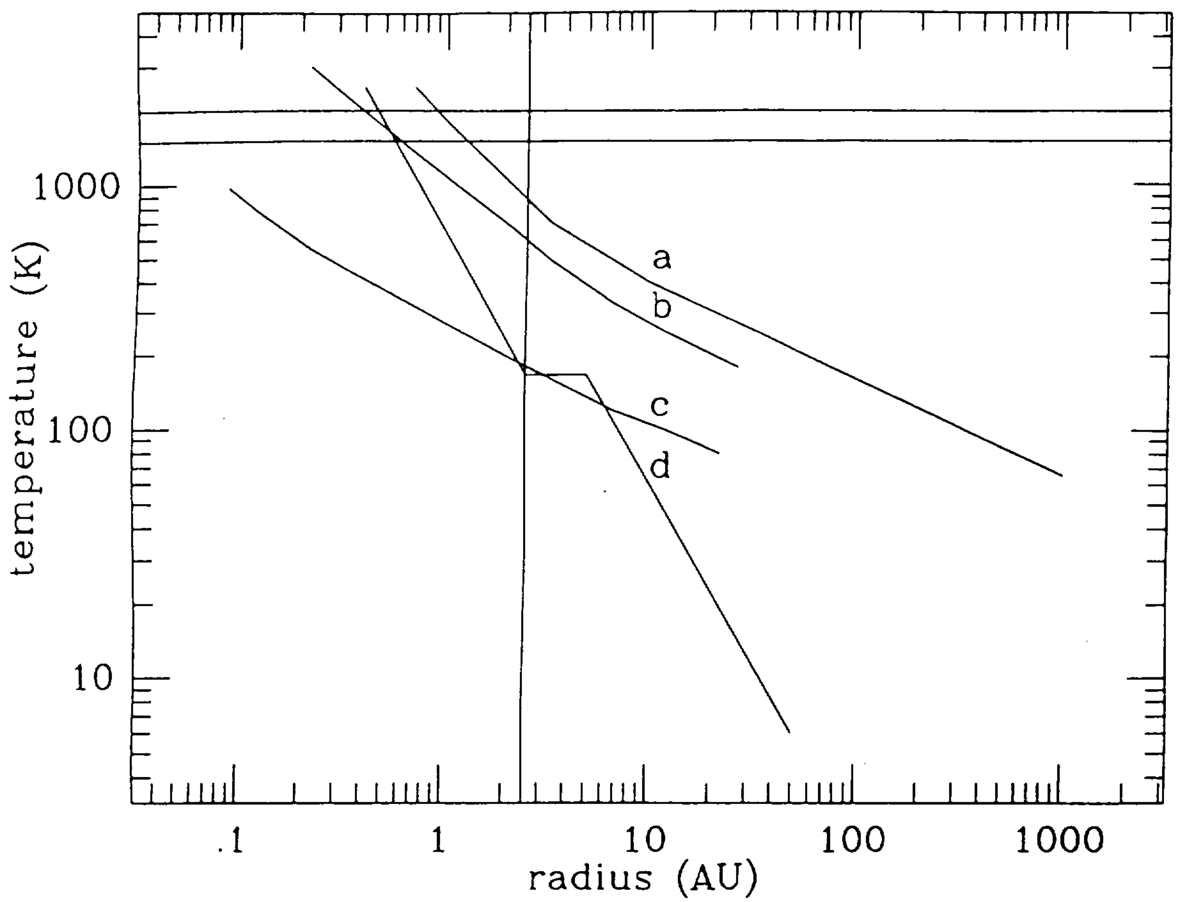

Figure 2 Temperature as a function of radius for several processes thought to be important in the Solar Nebula. (a) T of gas heated by the accretional luminosity of a $1M_{\odot}$ proto-sun (from Adams and Shu 1985). (b) T of dust grains slowed by frictional drag after entering the accretion shock around a $1M_{\odot}$ proto-sun, and (c) T of gas after heating by passage through the same accretion shock (both from Wood 1984; model L). (d) T at the midplane of a typical viscous accretion disk model of the Solar Nebula (from Wood and Morfill 1987). Horizontal lines depict approximate temperatures needed to melt or vaporize refractory silicate grains. The vertical line gives the location in the asteroid belt responsible for the bulk of meteorites impacting Earth.

The second hurdle is passage through the accretion shock. Wood's (1984) calculations of the post-shock temperature of the gas for a sample Solar Nebula (Figure 2) show that only modest temperatures ($\approx$ 250 K at 1 AU) are obtained by stopping the gas infalling at about 10 km s^{-1}. The dust grains pass rapidly through the shock, anyway, and are heated by frictional drag in the post-shock layers of the nebula. Wood also calculated this effect, and found that fractional drag can melt or evaporate silicate grains only well within 1 AU. Icy grains would be destroyed by frictional drag throughout most of the Solar Nebula. Hence only refractory silicate grains are likely to survive unscathed passage into the Solar Nebula.

Most models of the Solar Nebula in the last decade have been based on the assumption that a long-lived source of turbulence exists, leading to an effective turbulent viscosity capable of transporting angular momentum and mass through the nebula (reviewed by Wood and Morfill 1987). That angular momentum transport is necessary, even for a slowly rotating pre-Solar Nebula, is made evident by the fact that the sun contains some 99.9% of the mass of the Solar System, but only about 2% of the angular momentum. A viscous accretion disk evolves in the desired manner: angular momentum is transported outward by viscous stresses, allowing mass to move inward onto the proto-sun. Viscous dissipation of energy produces the nebula temperatures shown in Figure 2. Except for the very innermost regions of the nebula, these temperatures are less than those encountered by grains traversing the accretion shock. However, turbulence implies diffusion, and a fraction of the grains in a steady state viscous accretion disk will have been processed through the high temperatures in the innermost nebula, so some further reprocessing of silicate grains could occur.

Cabot *et al.* (1987) have studied in detail the physics of the convective instability thought to be the best candidate for driving the turbulence needed for viscous evolution. Cabot *et al.* uncovered several flaws which cast severe doubt on whether viscous accretion disks can reasonably represent the Solar Nebula, such as greatly reduced effective viscous stresses, and global instability of viscous disks to ring formation and possibly giant gaseous protoplanet formation.

One promising alternative to viscously-driven Solar Nebula models are models where gravitational torques between non-axisymmetric structures (such as bars and spiral density waves) provide the means for transporting angular momentum outward (Larson 1984; Boss 1984). Gravitational torques in even mildly non-axisymmetric nebulae can transport angular momentum on time scales of $\approx 10^4$ years (Boss 1987), and strongly non-axisymmetric structures such as bars can evolve on rotational period time scales (i.e., years). Dust grains in a turbulent nebula will undergo random walks which will tend to reprocess the grains and smooth out any large-scale heterogeneity in the grain populations. In a nebula evolving by gravitational torques, neither of these processes need occur, thereby enhancing the chances for survival of relict grains.

Refractory silicate dust grains may very well have survived their passage through interstellar clouds, proto-stellar collapse, and Solar Nebula evolution, but must have been incorporated into Solar System bodies if we are to find them today (else they would be lost by Poynting-Robertson drag).

The coagulation of dust grains within the Solar Nebula led to the formation of dust grains with sizes about 1 cm, concentrated in a thin dust disk in the midplane of the nebula. Gravitational instability of this dust disk is thought to have led eventually to the formation of roughly km-sized planetesimals which served as seeds for the latter accumulation of the terrestrial and gaseous planets (Wetherill 1980). Accumulation of the planetesimals occurred on an increasingly violent scale, because of the deepening gravitational wells, eventually leading to bodies massive enough to completely melt or vaporize incoming planetesimals even in the absence of heating by radioactive decay.

These processes are poorly understood at present, and so the precise point where all hopes for grain survival must be abandoned is not well known. Clearly the best chances for finding relict interstellar grains involve small bodies which appear to have experienced the least amount of planetary differentiation and processing: asteroids and comets are thus the primary candidates.

4. INTERPLANETARY DUST PARTICLES

Many of the interplanetary dust particles (IDPs) collected in the stratosphere are derived from comets, which probably represent the most primitive material that remains in the Solar System. It should be pointed out that while these are reasonable assumptions at present, they both remain unproven. There is not enough room for a full discussion of IDPs in this paper and interested readers are encouraged to see one or more of the following reviews (Fraundorf, Brownlee, and Walker, 1982; Sandford, 1987; Walker, Bradley and Sandford, 1987).

The collected particles are obtained from the stratosphere using impaction collectors mounted on the wings of high altitude aircraft. Typical particles have diameters in the 1 to 50 μm range, masses between 0.1 and 10 nanograms, and densities of about 0.7 to 1.7 g/cm^3. The extraterrestrial nature of these particles has been proven by a variety of techniques and it is clear that the collected dust is not from the same source objects that produce the known meteorite classes (Walker, Bradley, and Sandford, 1987). The particles are irregular in shape, dark in appearance, and have roughly solar abundances of elements. In general, they appear to be simple aggregates of micron and submicron grains.

The collected IDPs are not all similar but tend to fall into one of three classes dominated by the minerals olivine, pyroxene, and layer-lattice silicates (Sandford and Walker, 1985). The infrared spectra of these IDP types are consistent with a cometary origin (Sandford and Walker, 1985; Bregman *et al.*, 1987). The minerals in all of these particles are observed to be in chemical and mineralogical disequilibrium with each other (Bradley and Brownlee, 1986). This strongly implies that the constituent minerals in IDPs were formed in different locations and under different conditions. The minerals were then mixed together in a chemically unreactive environment and the resulting dust grains have remained unaltered since agglomeration. This implies that turbulence or some other mixing process was operant to some degree during some part of the evolution of the proto-Solar Nebula (or accretion disk).

Most of the silicates in IDPs are crystalline, although glassy or amorphous silicates are seen in many particles (cf. Bradley and Brownlee, 1986). It is not presently clear whether the amorphous silicates are in any sense more "primary" than the crystalline material. A minor fraction of the crystalline minerals show evidence of direct vapor phase condensation (Bradley, Brownlee, and Veblen, 1983), suggesting formation from a hot cooling gas. The formation process of the remaining crystalline silicates is unknown, but many of them may have formed by thermal alteration of amorphous precursor materials during Solar System formation.

IDPs contain carbon in a number of forms (Bradley and Brownlee, 1986), none of which have been completely characterized. Much of the carbon exists in the form of an amorphous matrix material surrounding the mineral grains within the particles. Many IDPs also contain some carbon in the form of "tarballs". These objects consist of very fine grained silicates embedded in a carbonaceous matrix. The appearance of these "tarballs" suggests that the IDPs are the result of at least two generations of agglomeration events, one to form the "tarballs" and a later one to form the collected IDPs. While rare, carbon is also seen in IDPs in the form of epsilon-iron carbides (Bradley, Brownlee, and Fraundorf, 1984). The production of such materials is characteristic of heterogeneous catalysis. This is a process whereby simple gaseous molecules like CO are reacted catalytically on grain boundaries resulting in the production of more complex hydrocarbons.

While the formation site(s) of the carbonaceous materials remain uncertain, it appears that at least some of this material must have an interstellar origin. This is suggested by the observation that many IDPs contain enormous deutrium enrichments (D/H up to 10 times the terrestrial value) (cf. McKeegan, Walker, and Zinner, 1985). These deuterium excesses are seen to correlate with carbon concentration, suggesting a hydrocarbon carrier phase. The carrier phase is observed to reside in submicron patches that are scattered randomly throughout the particles. No Solar System processes are known that can produce these large deuterium excesses, and their existence in IDPs and meteorites is generally taken to indicate the presence of an interstellar component. Several methods for producing the deuterium enrichments have been suggested. These include ion-molecule reactions at low temperatures (cf. Yang and Epstein, 1983) and selective photodissociation of interstellar polycyclic aromatic hydrocarbons (Allamandola, Sandford, and Wopenka, 1987). Whether the observed excesses are contained within actual carbon-rich interstellar grains embedded in the IDPs or whether they simply represent a "molecular memory" is not yet known.

Finally, it is worth noting that graphite has never been seen in IDPs. Since graphite is a fairly hardy mineral, and since the IDPs have clearly managed to collect other materials with interstellar signatures, we are forced to seriously consider the possibility that graphite is not a major component in interstellar space (contrary to most models of the interstellar medium).

We summarize this section with 3 comments. (1) Silicates in primitive Solar System materials (IDPs) are structurally and chemically diverse. A minor fraction of the silicate grains have been produced by direct vapor phase condensation from a hot gas, but the formation processes and locations responsible for most of the minerals are presently unknown. The majority of the minerals in IDPs are crystalline, although amorphous silicates are also seen. Many of the crystalline minerals may have been formed by thermal alteration of amorphous precursors. (2) Carbonaceous materials in meteorites and IDPs carry chemical and isotopic clues that suggest that they have formed by a variety of processes. These processes include (i) gas phase ion-molecule reactions at low temperatures, (ii) photolytic reactions involving interstellar polycyclic aromatic hydrocarbon molecules, (iii) heterogeneous catalysis of simple gas molecules on grain boundaries, and (iv) photolytic or ion-induced reactions in icy mantles. Processes (i) and (ii) are likely to have occurred in interstellar space while process (iii) probably occurred in the proto-Solar Nebula. Process (iv) could have occurred in either or both environments. (3) Ices deserve special attention, both in the laboratory and in astronomical observations since they (i) are likely sources and sinks of gaseous molecules in condensed regions, (ii) they mediate interesting chemistry (especially for "organic" materials), and (iii) they may have dominated the transport of some volatiles into the early protosolar cloud.

5. ISOTOPIC ANOMALIES IN METEORITES

This section provides a brief overview of some of the evidence for isotopic anomalies obtained from the study of primitive meteorites and their direct implications for: a) the time scale for formation of the Solar System and for last minute injection of freshly synthesized matter; b) specific nucleosynthetic components, distinct from the average mix in the Solar System; and c) the transport of interstellar matter and its incorporation in the Solar System without complete mixing and homogenization of distinct components.

The presence of general isotopic anomalies is now established for many elements, over a wide range of atomic numbers. In most cases, there have been developments both in experimental procedures and in the reexamination of theoretical nucleosynthetic calculations with the emphasis being placed on addressing the evidence provided by the new experimental data. The importance of the observations of isotopic anomalies is the possibility of identifying specific nucleosynthetic components that are distinct from the grand average of components reflected in the Solar System abundance curve. Multiple nucleosynthetic components are indeed required to interpret the observed anomalous isotopic patterns. The most distinctive components are defined by isotopic anomalies that are correlated by virtue of having been measured in the same samples and extending over a wide range of (Z, N) on the chart of nuclides. Combinations of effects in several of these nuclides produced by the same nucleosynthetic process have provided well-defined isotopic signatures. For example, isotopic anomalies in Ba, Nd, Sm and Sr imply distinct mixtures of r-, s- and p-process products in the exotic material as well as specific variations in the r-process yield.

The objects in which isotope anomalies have been found are refractory-element-rich inclusions in carbonaceous meteorites. These inclusions are enriched in Ca, Al, Ti and in refractory trace elements by factors of about 20 over the average Solar System abundances. The chemical composition of the inclusions is generally consistent with calculations of the chemical composition of the earliest condensates in a gas of solar composition. The inclusions range up to centimeters in size. A sub-class of these inclusions exhibits coarse crystals and petrographic textures which are consistent with crystallization of the inclusions from a liquid state. The crystals within an inclusion range in size up to a few 10^{-2} cm.

One of the major questions which has been addressed is whether the observed isotopic anomalies can be caused by remnant or preserved interstellar grains, produced in specific stellar environments and trapped in the inclusions after having been transported without loss of the chemical and isotopic imprint of the grains. In fact, the first observed isotopic anomalies were interpreted in terms of possible preserved grains which acted as carriers for the observed effects. To the extent that isotopic anomalies are observed for refractory elements (e.g. Ca, Ti) which are major stoichiometric constituents of the mineral phases in which they are contained, it is unlikely that the isotopic effects can be due to carrier grains which could have escaped identification. The isotopic composition of refractory elements residing in coexisting mineral phases in these inclusions is uniform, even though the chemical abundances are different. The contributions of carrier grains would not be expected to scale with the different chemical abundances in coexisting mineral phases. These observations do not provide any direct support for the presence of preserved and identifiable grains which act as carriers of the observed isotopic anomalies. It is generally agreed that these materials are products of high temperature processes in the Solar System and are not simply sintered agglomerates of interstellar grains.

Two general types of isotopic anomalies are observed: a) effects in specific isotopes which are known to be the daughters of short-lived radioactive nuclides; and b) general isotopic anomalies in nuclides for which no reasonable radioactive parent exists.

For case (a), it is important to establish whether the parent radioactive nuclide was incorporated live in the inclusion when the inclusion formed. In such a case, the data can provide time constraints for the production and transport of freshly synthesized materials and possibly a detailed chronology for the formation of the inclusions. In particular, effects due to nuclides with the shorter half-lives provide the tighter time constraints. The nuclides of interest are those with decay constants which are comparable to the time scales of astrophysical processes. The case for the presence of live ^{26}Al ($\tau_{1/2}$ = 0.7 $\times$ 10^{6} years) in the refractory inclusions appears well established. The isotopic effects appear as large excesses in ^{26}Mg which are precisely correlated with the Al/Mg ratio. Therefore, the excesses in ^{26}Mg are consistent with the decay of ^{26}Al with a fixed initial abundance relative to the stable ^{27}Al isotope, when the inclusions formed, corresponding to ^{26}Al/^{27}Al = 5 $\times$ 10^{-5}. The observed effects strongly suggest that ^{26}Al was present in the inclusions and that its decay occurred in situ. The evidence is based on analyses of bulk mineral separates, on analyses of individually extracted 100 μm crystals and on in situ analyses of μm-size areas of these crystals using an ion microprobe.

If the production ratio of ^{26}Al/^{27}Al is known, the time interval from production of ^{26}Al to its incorporation in Solar System objects can be calculated. Because of the exponential dependence and the short half-life of ^{26}Al, the time interval is relatively insensitive to the production ratio. It has been known that the production of ^{26}Al in supernova explosions is low. If the observed ^{26}Al/^{27}Al is due to a supernova, with a typical production ratio ^{26}Al/^{27}Al$\sim$10^{-3}, then more than 5% of the Al (including stable ^{27}Al) in the Solar System would be introduced by the last minute event which produced

^{26}Al. The lower limit of 5% for Al is obtained for the case of no dilution of the supernova debris by interstellar matter and requires the passage of no time between the production of ^{26}Al and its incorporation in the inclusions where its effects are found. For a supernova source, the time between production of ^{26}Al and formation of solid inclusions is less than ~ 3 m.y. These considerations have implied that supernovae are not adequate sources for ^{26}Al. Better sources for ^{26}Al are the H-rich envelopes of massive stars or novae. For a calculated production ratio as high as $^{26}Al/^{27}Al \sim 1$, a time scale of $\lesssim 10$ m.y. is obtained between production of ^{26}Al and the formation of at least small bodies in the Solar System. Dilution of the ^{26}Al and ^{27}Al produced just before incorporation into the Solar System with "old" ^{27}Al would yield a time scale closer to a few 10^6 years.

The case for the incorporation of exotic ^{26}Al in the Solar System from the interstellar medium is supported by the recent observation of a diffuse source of ^{26}Al in the galaxy. However, we may also consider the case for a local, i.e., within the Solar System, source of ^{26}Al. This would require the irradiation of a dust cloud or of planetary surfaces by energetic solar protons with a fluence of $10^{21}-10^{22}$ protons/cm^2 (E $\gtrsim$ 30 MeV). The question of importance is whether the early sun went through an intense T-Tauri phase. The resolution of this issue lies with theoretical calculations and with further investigations of nuclides in meteorites which are sensitive indicators of proton irradiation effects. A recent calculation (Wasserburg and Arnould 1987) addresses the possibility of production of ^{26}Al and of ^{53}Mn ($\tau_{1/2} = 3.6 m.y.$) during the same irradiation. The presence of ^{53}Mn in refractory inclusions is based on recent Cr measurements by Birck and Allegre from the University of Paris. The inferred abundances of ^{26}Al and ^{53}Mn can be made consistent with such an irradiation.

From the study of effects due to now extinct, short-lived nuclides, an injection of freshly synthesized matter is required. The level of contribution corresponds to about 10^{-4} of the material in the Solar System. The late stage nucleosynthesis must have occurred within $\sim 3 \times 10^6$ years before Solar System formation. This implies a direct connection in time between the early Solar System formation and the interstellar medium.

We now consider the more general isotopic anomalies. There are a few elements, e.g. O, Ti, Cr, that appear to show endemic isotopic anomalies. For these elements, most inclusions show small isotopic anomalies. Up to now, for all other elements (e.g., Sr, Ba, Nd, Sm), isotopic anomalies exist only in two refractory inclusions that have been labeled FUN. (FUN is the acronym for Fractionation and Unknown [provenance] Nuclear [effects].) Furthermore, the FUN inclusions show isotopic patterns for Ti and Cr which are distinct from the endemic anomalies for these elements in non-FUN inclusions. Therefore, there exists an acute shortage of materials that can provide us with the evidence of general isotopic anomalies. It is also evident that our information is obtained from an extremely limited class of objects.

The FUN inclusions were first identified by the observation of substantial isotope fractionation effects for Mg and O, coupled with general isotopic anomalies for these elements. The isotopic fractionation effects can be produced by kinetic effects during condensation in the Solar Nebula or during high temperature distillation of already condensed materials. While the correlation of F and UN effects remains unclear, the observed isotopic effects have been well characterized and can be attributed to different nucleosynthetic components. Some of the major conclusions are:

1. Based on correlated effects in the most neutron-rich isotopes of Ca, Ti and Cr (^{48}Ca,^{50}Ti,^{54}Cr), one requires a component produced by neutron-rich equilibrium burning. This component provides constraints both on the nucleosynthetic process and on the mechanisms for supernova explosion, the ability to eject material from near the core of a supernova, and the transport of this material without substantial chemical fractionation of the elements (Ca, Ti, Cr) which have different physical and chemical properties.

2. Based on measurements of Ba, Nd and Sm, an excess r-process component has been identified from observed excesses in those isotopes (of all three elements) which have r-process contributions, as compared to isotopes which are produced only or dominantly by the s-process. The inferred exotic r-process yield is slightly different than the average r-process composition reflected by the Solar System abundance curve.

3. Based on data on Sm and Nd, it is concluded that the production of p-process isotopes (in particular, ^{144}Sm) is decoupled from the production of the r-process isotopes. The observations show that, in one inclusion, there is an excess of p-process and r-process isotopes relative to the s-process isotopes; in a second inclusion, there is only an excess in the p-process isotope ^{144}Sm and no effects in the r-process isotopes. While the astrophysical site of the p-process is not established, this constraint is important.

The major questions of importance which require attention are:

a) further experimental determination of exotic components in Solar System materials;

b) theoretical investigation of nucleosynthetic processes, especially to address specific observed isotopic components;

c) investigation of the formation and evolution of interstellar grains;

d) study of transport mechanisms in the interstellar medium and of the conditions which could permit the incomplete homogenization of materials with characteristic isotopic and chemical compositions;

e) theoretical and experimental study of the effects of a T-Tauri phase on condensates in the Solar System; and

f) investigation of the time scale for transport of materials and incorporation in the Solar System.

The isotopic effects reviewed very briefly here have been obtained by work over the last fifteen years. This is an active area, where review papers quickly become dated. General reviews can be found in Wasserburg and Papanastassiou (1982) and in Papanastassiou (1985). The more recent work on Cr is reviewed in Birck (1987) and in Papanastassiou (1987).

6. CONCLUSIONS AND FUTURE PROSPECTS

We have seen that studies of nearby star-forming regions are beginning to reveal the first signs of protoplanetary disks. Studies of interstellar and interplanetary grains are starting to provide clues about the processing and incorporation of matter into the Solar System. Studies of meteorites have yielded isotopic anomalies which indicate that some of the grains and inclusions in these bodies are very primitive. Although we have not yet detected a true interstellar grain, some of these materials have not been extensively modified since their removal from the ISM. We are indeed close to seeing our interstellar heritage.

The overlap between astronomical and Solar System studies is in its infancy. What future experiments, observations, and missions can be performed in the near future that will greatly enhance our understanding of star formation and the formation of the Solar System?

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