SUMMARY OF JOI NT DISCUSS1ON #17:

DUST AROUND YOUNG STARS: HOW RELATED TO S01 .AR SYSTEM I)[JST?

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ABSTRACT

This Joint Discussion explored the links between properties of interstellar (IS) dust, the evolution of dust in young stellar objects (YSOs), and primitive solar system dust. Spectral observations and gas phase depletions indicate that there are several components of I S dust. Grain growth by accretion and coagulation takes place in dense, star-forming regions. There is growing evidence that accretion disks surround man y YSOs, but onl y a fraction o f T Tauri stars have disks massive enough to be protoplanetary. Comets contain a signi ficant fraction of organic material, but it is not yet well characterized. The ratio of CO : H_2O implies that comets accreted from 1 S ices, not gas. IS grains in meteorites, identified by their anomalous isotopic abundances, show that the solid grains in the protosolar nebula came from a variety of stellar sources. Glassy silicate grains common in interplanetary dust particles show evidence for exposure to high radiation doses in the interstellar medium. ‘J’bus, there is the exciting prospect of studying in the laboratory the physical processes to which 1 S grains have been subjected.

1. INTRODUCTION

Study of the dust in circumstellar disks around young stars is currently an extremely active area in astronomy. Much recent observational and theoretical work is giving us a clearer picture of the physical conditions in dust disks and their evolutionary progression. The short time scale for grain destruction in the diffuse interstellar medium means that substantial grain growth occurs in dense clouds, Laboratory experiments on low-temperature ices are improving our understanding of the chemical processes in grain mantles and the formation of organic material.

A portion of the dust in disks around young stars ultimately may be incorporated into planetary systems. "Thus, study of the dust in our own solar system complements the remote sensing of protostellar regions and aids in reconstructing the evolutionary history of the dust. Technical advances now allow analysis of individual micrometer or smaller grains in interplanetary dust particles and primitive meteorite samples. Isotopic anomalies and patterns of crystal growth in these particles are yielding tantalizing clues about the interstellar material incorporated into these solar system samples.

This Joint Discussion was initiated by Commission 21 *Light of the Night Sky* and Commission 34 *Interstellar Matter* in order to tie together these new discoveries and explore the evolution of dust from the interstellar medium to the solar system. This article summarizes the presentations and discussion.

2. DUST DISKS AROUND YOUNG STARS

2.1 *Protoplanetary Disks Around Pre-Main Sequence Objects*

Our understanding of the way the solar nebula evolved rests, in part, on the study of the nature and evolution of young stellar objects (YSOs). The pre-main sequence '1' Tauri stars are thought to be the progenitors of solar mass stars. The 1 Ierbig Ae/Be stars are more massive and are the likely progenitors of A-type stars, including those with circumstellar disks such as a Lyr and β Pie.

Many YSOS exhibit an infrared excess, indicating the presence of warm dust. They can be classified according to the spectral energy distribution of the infrared excess (1 ,ada 1987; Wilking, Lada & Young 1989; André & Montmerle 1994). Adams, Lada & Shu (1 987) have interpreted the infrared spectral classes as an evolutionary sequence. in their models, Class I objects, with spectral energy distribution rising toward longer wavelength, correspond to the infall phase. "l'he protostar and an accretion disk are embedded in an optically thick infalling dust envelope. Class 11 objects arc visible protostars with nebular disks. These are classical T Tauri stars. The infrared excess is thermal emission from dust in the optically thick disk, heated by the central star. Class 111 objects, with small, if any, infrared excess, arc the weak-lined or "naked" '1' Tauri stars with a remnant optically thin disk.

'1'here arc several indirect arguments for the existence of disks around T Tauri stars: Disks arc the natural outcome of the collapse of a rotating cloud core (Tereby, Shu & Cassen 1984). The forbidden emission lines in many T Tauri stars arc blue-shifted only, consistent with the occultation of the receding, red-shifted wind by a disk ~ 100 AU in size (Appenzeller *et al.* 1984; 1 Edwards et *al.* 1987). Maps of the polarization around YSOS can be explained by multiple scattering with an optically thick disk (Bastien & Menard 1988, 1990), A large amount of circumstellar material around some optically visible stars is inconsistent with spherical geometry (Beckwith *et al.* 1990).

1 Direct evidence for disks has been difficult to acquire, because of their small angular size. Images from the refurbished Hubble Space Telescope have resolved circumstellar disks surrounding

56 young stars in the Orion Nebula (O'Dell & Wen 1994). O'Dell & Wen estimate lower limits to the disk masses of - 2 x 10^{28} g, or - 10-5 solar masses, M_o. The minimum solar nebula mass necessary to form the planetary system was -0.01 M_o. Thus, abetter mass estimate of the Orion sources is needed before one can say that the disks are protoplanetary.

Intimating the total mass of dust in disks is not possible from the infrared fluxes, because the sources are optically thick in the infrared, At millimeter wavelengths, disks are optically thin and cold dust can be detected, allowing the dust mass to be estimated from the observed fluxes. The value of K, the mass absorption coefficient, is the largest uncertainty in the mass estimates. Two recent 1.3 mm surveys have provided statistics on the mass of circumstellar material (Beckwith *et al. 1990;* André & Montmerle 1994). About 30°/0 of classical 1' Tauri stars have disk masses above the minimum solar nebula mass of 0.01 MO; only these can truly be classified as protoplanetary disks, For Class 1 sources, André & Montmerle find masses of 0.015-0.15 M_o, too low to represent the main infall stage as modeled by Adams *et al.* (1 987). Several objects which have strong mm fluxes but are invisible in the mid-infrared have masses ~0.5 MO; these objects apparently represent the main accretionary phase.

Sources with circumstellar mass > 0.01 MO will be optically thick at λ < 100 pm. The minimum infrared excess for an optically thick disk can be calculated as a function of L_*. Thus, the observed infrared excess above the reddened photo sphere of T Tauri stars can be used to determine the frequency of optically thick disks with M > 0.01 M_o (Skrutskie *et al.* 1990; Strom *et* al. 1993). These authors find that 30% - 50% of young (< 3 x 10^6 yr) stars with $M_* < 3M_0$ have infrared excesses indicative of optically thick disks. Almost no optically thick disks arc found for stellar age ≥ 107 yr. Very few sources have been found with infrared excess intermediate between optically thick and optically thin excesses. Thus, disk clearing must proceed rapidly. Skrutskie *et al.* give a time scale of -3 x 10^5 yr.

in summary, there is substantial evidence that disks surround a sizeable fraction of low-mass YSOS during at least part ofthcir evolution. However, millimeter surveys suggest that only about 30 % of classical '1' Tauri stars have protoplanetary disks; that is, disks more massive than the minimum solar nebula mass of ~0.01 M_o.

2.2 *The Dust in β Pictoris Systems*

The IRAS satellite detected far-infrared emission surrounding three nearby main sequence A stars, α Lyr, α PsA, and β Pie, indicating that these stars are surrounded by solid grains at temperat ure T - 100 K (Backman & Paresce 1992 and refs. therein). Subsequently, about 100 main sequence stars of all spectral types with similar infrared excesses have been found in the IRAS database. A chronographic image of β Pic at λ 0.89 μm clearly showed an edge-on disk of material extending to 1000 AU from the central star (Smith & Terrile 1984). The lifetimes of orbiting grains in the disks duc to l)oynting-Robertson drag and collisions are short compared to the estimated ages of the stars (108 years for β Pic to 4 x 1 Ox years for α Lyr). '1'bus, the dust disks in these three systems are not primordial, but must bc replenished. Dust release from comets is onc plausible source,

The spectral energy distribution of the infrared excess depends on the temperature distribution and emissivity (hence size) of the grains in the disk, Thermal models lead to characteristic grain sizes of-1 00 μm for α Lyr, -10-50 μm for α PsA, and ~ 1 pm for β Pic. The discovery ofa silicate emission feature in β Pic is further evidence for micrometer grains in the disk (Knacke *et al.* 1993). From submm maps Zuckerman & Becklin (1 993) derive minimum disk masses on the order of 0.01 1 Earth masses for α Lyr and α PsA and ~0.1 Earth mass for β Pic.

The minimum wavelength of excess flux implies a lack of hot grains in these systems. Therefore, the inner region around the central star must have a much lower density of material. The extent of this region in α 1.yr, α PsA, and β Pic is comparable to the planetary region of the solar system. Since Poynting-Robertson drag would tend to fill in this region over time, an efficient removal mechanism is required. Sweep-up by planets is a possible explanation.

Fundamental questions about the disks in β Pic systems remain to be answered:

1. Is there an evolutionary connection between circumstellar disks around young stellar objects and the disks in β Pic systems?

2. What is the relationship between dust disks and planetary systems? Do the dust disks represent successful planetary formation or failed planetary formation?

3. What is the reservoir for replenishing the dust disks? Arc these systems surrounded by a cloud of comets?

3. INTERSTELLAR DUST

The physical properties of interstellar (IS) grains arc inferred from the 1 S extinction curve, polarization, scattering of xrays, thermal emission, spectral features, and 1 S gas depletions compared with cosmic abundances.

The ultraviolet, optical, and infrared observation is lead to a picture of several grain populations. This set should be viewed as a "working hypothesis", not a final answer, for there arc still problems and inconsistencies and not all researchers agree with the following list (Greenberg 1989; Mathis & Whiffen 1989; Rowan-Robinson 1986, 1992; Duley 1987).

1. a ~ 0.01 μm silicate and carbon grains responsible for the far-ultraviolet extinction

2. *a* -0.01 μm graphitic carbon to produce the 0.2175 μm **bump**

3. very small grains (0,0005 - 0.002 pm) producing the infrared emission bands and non-equilibrium thermal emission

4. a -0,12 μm grains composed of silicate and carbon giving rise to the visible and near-infrared extinction.

The population of grains causing the visual and near-infrared extinction and polarization must be elongated and aligned to account for the obsei ved polarization. The wavelength of maximum polarization, λ -0.55 μm in the diffuse IS medium, implies grain radii *a -0.1 pm.* The linear and circular polarization are best fit by a material such as silicate that is not strongly absorbing. Absorbing grains must also be present, because silicates alone would give too high an albedo. Mathis *et* al. (1 977) pictured the silicate and carbon grains as bare and homogeneous, with a size distribution $n(a) - a^{-3}5$. Mathis & Whiffen (1 989) proposed that IS grains arc fluffy conglomerates of small silicate, amorphous carbon, and graphite particles.

Greenberg (1982, 1989 and refs. therein), recognizing that a typical IS grain cycles many times between molecular clouds and the diffuse ISM, de~'eloped a model of core-mantle grains. Within molecular clouds, icy mantles composed of the abundant elements H, C,N,O accrete on existing silicate cores. When the grains arc subsequently exposed to UV radiation, the mantles arc photoprocessed, leaving an organic refractory residue. When the grain cycles back into a molecular cloud, another layer of ices is deposited, and the process repeats. '1'bus, grains in the diffuse ISM can have mantles of differing thickness and differing stages of photoprocessing.

A major issue is what type of grain structure survives best in interstellar shocks. Do tbc photoprocessed mantles protect the silicate cores, as Greenberg proposes? Does the fluffy structure protect the inner parts of conglomerate grains as Mathis & Whiffen propose?

Any model of IS grains has to be consistent with cosmic elemental abundances. Assuming that cosmic abundances arc the same throughout the lSM, we can infer the dust composition by observing the extent to which gas phase abundances are depleted relative to cosmic abundances. The most refractory elements Al, Ca, and Ti are depleted by factors up to -1000, while Fe, Cr, and Ni are depleted by a factor of-100 (Jenkins 1989). Sofia *et al. (1* 994) have reexamined the gas phase depletions for the major elements using new data from the Hubble Space Telescope ultraviolet spectrograph. Iron has the largest fraction of its atoms locked up in dust (≥83%), while ≥34% of Si is in the dust phase. Oxygen is the most abundant element in the dust by number (because of its high cosmic abundance), greater than the sum of all other atoms. The sum (Fe+Mg):Si is, in many cases, higher than can bc accounted for by silicates of olivine $(Mg,Fe)_2SiO_4$ or pyroxene $(Mg,Fe)SiO_3$. ‘1’bus, some of the Mg and Fe must form oxides or metallic Fe.

Grains condense in the circumstellar environment around mass-losing AGB stars. Based on the mass loss rates from AGB stars, the time scale for replenishing the dust in the ISM is a few times 109 years. But the diffuse ISM is a harsh environment for a tiny grain. Fast shocks associated with supernovae remnants efficientl y destroy grains by thermal and non-thermal sputtering and co] lisions (Scab & Shull 1986). McKee (1 989) and Jones *et al.* (1994) derive a destruction lifetime of -4 x 108 yrs, far shorter than the timescale for replenishment from AGB stars.

‘1’bus, not only arc grains heavil y processed in the 1 SM, but also significant grain growth must occur in the ISM. Since grain growth occurs primarily in dense regions, there must bc rapid exchange bctwccn molecular clouds and the warm neutral medium,

Clearly, as observational data expand, our model of 1 S grains has to bccomc more sophisticated. Some of the present questions arc:

1. How much carbon is present in the dust? Is it sufficient to cover the graphite, PAH, and amorphous carbon in the grain models? What is the most common form of carbon?

2. Is the 0.2175 μm extinction bump due to graphite? Where does the graphite form?

3. How do very small grains survive without being destroyed or incorporated into larger grains?

4. How does a significant component of oxides affect the "working hypothesis" model of grain populations?

5. What is the size distribution and physical structure of the "classical" grains responsible for the visual extinction?

6. How do grains survive shocks?

4. DUST IN THE SOLAR SYSTEM

4.1 Cometary Dust

Comets formed in the outer solar nebula, where the temperature remained low enough that intact interstellar grains could have been incorporated into the comet nuclei.

Time-of-flight mass spectrometers on Halley space probes measured the elemental composition of submicron sized dust particles in the coma (Kissel *et al.* 1986). A dust component rich in refractory organic material was discovered, the so-called CHON particles. Infrared and submillimeter spectra of Halley indicated that a variety of organic molecules were present. Chief among the presumed solid state features was a broad unidentified feature at 3.36 μm, subsequently seen in a number of comets. Reuter (1992) has shown that up to half of the flux in the 3.36 μm feature may be due to methanol; the source of the remaining flux is unknown.

Some comets exhibit a strong silicate feature with a distinct peak at 11.2 pm, attributed to crystalline olivine particles, in addition to a broader maximum near 9.7 μm (Hanner *et al.* 1994a,b). Since the 11.2 μm peak is not seen in spectra of IS dust, the olivine most likely formed at high temperatures in the inner solar nebula, in which case there must have been considerable radial mixing in the solar nebula to transport these grains to the region of comet formation.

The polarization phase curve, P(θ), has been measured for a number of comets (Dollfus *et al.* 1988; Levasseur-Regourd & Hadamcik 1994 and refs. therein). All of the comets have negative polarization at small phase angles. However, they separate into two distinct groups having P_{max} ~10% or *-25%* near *90°* phase. The higher P_{max} correlates with comets that display a strong silicate feature, while the comets with lower P_{max} have weak or no silicate emission. It is not clear whether differences in size distribution or composition are responsible.

Fundamental questions remain about how cornets fit into the evolutionary picture. Some of these quest ions can only be answered from direct sampling of cometary dust:

1. What is the heterogeneity among comets and within one comet nucleus?

2. What is the chemistry of the organic material?

3. Can the differences among comets in optical properties such as polarization be explained solely by differences in particle size or are compositional differences required?

4. Is the material in comets "local"; i.e., local to the solar nebula at a given heliocentric distance, or is it a mixture of material from high and low temperature regions of the nebula?

5. "To what extent are intact IS grains preserved in comets?

4.2 *Interplanetary Dust*

The earth is situated within a flattened cloud of interplanetary dust. Since the dynamical lifetime of the dust is short compared to the age of the solar system, the dust cloud must be continually replenished. Comets and asteroids are the main sources for replenishing the dust cloud. Dust bands (associated with asteroid families) and dust trails (associated with comets) seen in the *IRAS* sky flux maps provide evidence of these sources.

The zodiacal light brightness viewed from earth is an integral over the scattering by all dust particles along the line of sight. Inversion techniques have been applied to extract the local properties of the dust from the line-of-sight integral (Levasseur-Regourd *et al.* 1990), At least two distinct dust populations with differing optical properties and orbital inclinations are required to fit the optical data. Thermal emission from the interplanetary dust has been measured from rocket flights and from the *IRAS* and COBE satellites. At 5-50 pm, the emission is the strongest component of the diffuse sky brightness beyond the terrestrial atmosphere.

Dust detectors have flown on a number of spacecraft in earth orbit and solar orbit. The mass, speed, and direction of the impacting particle can be measured (Grün *et al.* 1985). There is evidence for different dust populations with different orbital characteristics, confirming the inferences from remote sensing. The dust experiment on the Ulysses spacecraft has detected interstellar dust particles at 5 AU that are streaming through the solar system from the apex direction of solar motion (Grün *et al.* 1994).

interplanetary dust particles (IDPs) in the size range 5-50 μm are routinely collected in the stratosphere, having survived atmospheric entry without destructive heating (Bradley *et al.* 1988). The chondritic aggregate IDPs are fine-grained aggregates of micrometer-submicrometer sized particles of silicate and carbonaceous material, with chondritic abundances of the major rock-forming elements and high carbon content. Pyroxene whiskers and platelets that bear the signatures of direct vapor phase condensation have been found (Bradley *et al.* 1983).

Pyroxene-rich IDPs are the most likely candidates for cometary particles, based on their porous structure, high carbon content, and relatively high atmospheric entry velocities. Yet neither the pyroxene- rich nor any other single class of IDPs can match the shape of the silicate feature seen in cometary spectra (Sandford & Walker 1985; Bradley *et al.* 1992).

The most striking feature of the porous aggregate IDPs is that they arc unequilibrated mixtures of high and low temperature condensates even on a submicrometer scale. Does this reflect efficient mixing of small grains formed in different regions of the solar nebula and transported to the region of comet formation? Or, are these submicrometer units truly interstellar grains? A major component of these IDPs arc compact grains 0.1-0.5 pm in size, given the descriptive name of GEMS (Glass with Embedded Metal and Sulfides). Bradley (1 994) argues that the GEMS show evidence of high radiation doses that could have occurred only in the ISM. If the GEMS are truly interstellar “dirty silicate” grains, wc have the exciting prospect of studying in the laboratory the physical processes to which 1 S grains have been subjected

4.3 *Interstellar Material in Meteorites*

Meteorites arc an abundant source of extraterrestrial material that may contain IS components. Since meteoritic material has been subjected to considerable solar system processing, isotopic anomalies arc the only sure tracers of interstellar grains; these identifications rely not on one isotopic ratio, but a pattern. Most of the analysis has been focused on carbonaceous chondrites, the most “primitive” meteorite class. Four types of IS grains have been identified, based on non-solar isotope ratios in C,N,O, Mg, Si, “l’i, and the noble gases Nc, Kr, Xc (Anders & Zinner 1993). Microdiamonds 0.001 μm in size arc the most abundant IS component yet isolated, comprising -400 ppm of the meteoritic material. They contain xenon enriched in both the light (^{124}Xe, ^{126}Xe) and heavy (^{134}Xe, ^{136}Xe) isotopes, indicative of both p-process and r-process nucleosynthesis occurring in supernovae. SiC grains, have been found at the 7 ppm level. 'l'heir size ranges from 0.3 -3 pm, although a few as large as 10 μm are seen. The xenon isotopes ^{128}Xe - ^{132}Xe follow a pattern indicative of s-process nucleosynthesis in AGB stars. Sever al forms of graphite have been identified in primitive meteorites at the 2 ppm level, but only the spherical grains 0.8 -7 μm in size have anomalous C isotopes proving their IS origin. Graphite is presumed to be common in the ISM as the source of the 0.22 μm extinction bump. However, the IS graphite particles are -0.01 pm, in contrast to the large graphite grains in the meteorites. Corundum grains (Al_2O_3) show a large range in their oxygen isotopes that seem to require origin in stars of differing mass and initial $^{16}O/^{18}O$.

In addition to these grains, another component of IS material exists in meteorites, associated with anomalous deuterium/hydrogen ratios (Zinner 1988). 'l'he anomalies have been traced to acid-insoluable organic residues, constituting only a small fraction of the meteoritic material. D/H anomalies also have been found in IDPs (McKeegan *et al. 1985).*

The meteoritic evidence leads to two important conclusions. First, the solid grains in the protosolar nebula came from a variety of steller sources, including supernovae and AGB stars with a range of metallicities. Second, some grains did survive the harsh 1 S environment and retained the imprint of their formation. As laboratory analytical techniques improve, wc can expect more interesting results, especially if methods arc found to identify IS gr ains with normal isotopic abundances, such as the GEMS found in IDPs.

5. EVOLUTION OF DUST FROM THE INTERSTELLAR MEDIUM TO THE SOLAR NEBULA

5.1 Evolution of Dust in Dense Regions

The optical and physical properties of grains do not remain static over time. Grain growth and destruction, structural transformations, and chemical evolution all affect grain properties. The rate of grain destruction in the diffuse IS medium implies that considerable grain growth must take place in dense clouds. Numerous observational studies of the extinction and polarization have shown that the mean grain size is larger within dense clouds,

Grain growth can occur by accretion or coagulation. The higher gas depletions and the presence of the 3.08 μm water ice absorption feature (and other spectral features of ices; section 5.2) indicate that accretion of icy mantles has occurred in dense clouds. Yet, some regions show evidence of larger grains, but lack the 3.08 μm ice feature. '1'bus, grain growth by coagulation must also be important in dense regions. Sticking of bare grains occurs only at velocity $\lesssim$ 1 m/s (Tielens 1989). Sticking is successful at somewhat higher velocities if the grains arc ice-coated. '1'bus, accretion enhances coagulation.

Wc expect the dust in dense clouds, then, to have a variety of shapes, sizes, and compositions, inducting fluffy aggregates. The optical properties of such heterogeneous aggregates arc difficult to specify. Two papers have recently presented working models for the dust optical properties in the dense regions from which protostars form. Preibisch *et al.* (1 993) used three dust components: amorphous carbon, small silicate grains, and silicate cores with dirty ice mantles. Pollack *et al.* (1994) base their model, in part, on the chemical composition of primitive solar system materials. In contrast to other models, organic materials arc the main reservoir for carbon. Metallic iron is a major absorbing species and troilite (FeS) is also explicitly included, along with glassy olivine and orthopyroxene.

S. 2 *Evolution of Ices and Organic Compounds*

"1'here is ample evidence that icy mantles accrete on grains in cold dense regions. Infrared spectroscopy of sources located within or behind dense clouds reveals many absorption features due to vibrational modes in ices and organic species. The prototypical source is the embedded protostar

W33A. Laboratory investigations of the spectra of low-temperature ices and ice mixtures, before and after irradiation, have led to the identification of the major species, but important ambiguities remain (d'] Iendecourt et *al.* 1986; Tielens & Allamandola 1987; Grim *et al.* 1989).

The strong feature at 3.08 μm due to the 011 stretching vibration in H_2O ice is seen in many embedded sources, consistent with water ice as the main constituent of grain mantles.

Solid CO has a band at 4.67 μm and this feature has been detected in the spectra of a number of embedded protostars (Lacy *et al.* 1984; Geballe 1986; Tielens *et al.* 1991). The astronomical feature usual] y has two components, a narrow absorption at 2140 cm^{-1}, and a broader absorption centered at 2134 cm-'. The broader component arises from CO mixed at concentrations of a few percent in a polar ice, probably water ice, under reducing conditions. The narrower band at 2140 cm^{-1}, however, must be due to CO in a non-polar ice, such as pure CO, CO_2, N_2, or O_2 in an oxidizing environment (Sandford *et al.* 1988; Tielens *et al.* 1991).

The abundance of methanol (CH_3OH) in grain mantles is controversial (e.g. Allamandola *et al.* 1992; Schutte *et al.* 1991; Skinner *et al.* 1992). Methanol could form via grain surface reactions when atomic H is available or as a product of UV photolysis or ion irradiation (although H_2CO is the favored product). The 3.53 μm absorption band in W33A has been identified as solid methanol by Grim *et al.* (1991). They derive a methanol abundance of 7% relative to water ice, But, if the 6.85 μm absorption band in the spectrum of W33A is due to methanol, an abundance of ~50% relative to water is required. More likely, the 6.85 μm band arises in more complex organic species (Tielens & Allamandola 1987; Grim *et al.* 1989). Even with the uncertainties, methanol is the second most abundant molecule along the line of sight to W33A.

1 Extensive laboratory experiments have been carried out over the last 15 years to understand the physical anti chemical processes affecting evolution of grain mantles (e.g. Greenberg 1982, Grim

et al. 1989; d'Hendecourt *et al. 1986;* Tielens & Allamandola 1987; Moore & Donn 1982; Strazzulla & Johnson 1991; Allamandola *et al.* 1988).

The most important result of the experiments is the demonstration that UV photo] ysis or ion bombardment of low-temperature ice mixtures can lead to the formation of chemically complex organic residues that arc stable when the sample is warmed to room temperature. The residue produced by UV photolysis of an ice mixture consisting of 1120, NH_3, and CO contains a variety of organic species with up to three C atoms. They are rich in O and N, containing subgroups such as -OH, NH_2, and C=O (Briggs *et al.* 1992). Perhaps such material is related to the abundant oxygen-rich organic species that were detected in Halley's coma (section 4.1).

Chemical reactions can take place spontaneously when the accreted icy mantles are heated, producing new chemical species. For example, Schutte *et* al. (1993) have observed that, when H_2CO and at least a trace of NH_3 arc present in the initial ice mixture, heating causes the H_2CO to form chain polymers of polyoxymethylene (POM) and its derivatives.

For gas density - 104 cm^{-3}, all the gas phase molecules (except H_2) should accrete onto grain surfaces in - 10S yrs, a timescale short compared to the ages of molecular clouds. Onc possible mechanism to replenish the gas phase is explosive desorption of grain mantles when irradiated ices are heated above -26 K (Schutte & Greenberg 1991 and refs. therein).

The importance of UV and other energetic processing of the ices within dense clouds remains unclear. Future observations of the very strong 4.46 μm feature of CO_2, abundantl y produced in the laboratory by photolysis of' ices containing CO and 1120, with the European Infrared Space Observatory (1 SO) will shed new light on this issue. A related issue is the efficiency with which organic material is produced in the ice mantles. Sensitive high-resolution spectroscopy of the 5-

8 pm region as may be obtained by 1S0 is necessary to search for organic molecules that might be mixed into the ice mantles.

5.3 *Evolution of Dust in Protoplanetary Disks*

Accretion disks created by infalling material from the protostellar envelope are now considered to be a natural part of the evolution of a solar-mass star (section 2.1). Disk masses are typically 0.01 -0.1 MO and disk sizes arc< 100 AU. An important factor in the subsequent evolution of protoplanetary disks is the presence or absence oft urbulence. The most likel y cause of turbulence is a superadiabatic vertical temperature gradient, leading to vertical turbulent convection. Such a steep thermal gradient is due to opacity, which inhibits radiative heat flow.

Although dust is a small fraction of the total nebular mass, it exerts a strong influence on the evolution of the nebula, because dust is the source of the opacity and the opacity determines whether thermal convection will occur. Yet, the composition, size distribution, and optical properties of the initial dust population feeding the accretion disk are not wc] l known (section 5.1). Rosseland mean opacities have been computed by Pollack *et al.* (1994) and Preibisch *et al.* (1993) among others.

The opacity will increase as grains begin to grow to a size comparable to the wavelength, causing an increase in turbulent convection. Turbulence generates size-dependent differential dust velocities leading to grain-grain collisions and rapid grain growth, as larger particles sweep up smaller ones. I'bus, turbulence accelerates grain growth and grain growth increases opacity, creating stronger convective turbulence. This tight coupling, between turbulence and grain growth has to be addressed in any realistic accretion disk model (e.g. Mizuno 1989, Sterzik & Morfill 1994).

Although turbulence fosters grain growth, it prevents the dust from settling to the central plane. A critical stage is reached when grains have grown large enough (size >> λ) that opacity decreases and the nebula becomes optically thin. Then the nebula can cool by radiation and thermally-driven turbulence ceases. "l'he dust particles, which have already grown to mm-cm size, rapidly settle to the mid-plane, forming a thin dust layer in which Goldreich-Ward (1 973) gravitational instability can develop, leading to the growth of km-sized planetesimals.

One important question is the extent that dust can be radially transported in the disk from the warm inner nebula at R $\leq$ 1 AU to the region of come formation at R > 1() AU. Cuzzi *et al. (1993)* have computed that small grains entrained in the outflowing gas near the mid-plane of the solar nebula could drift radially outward - 2-5 AU before being accreted onto larger particles. Grain growth was a rapid process (Weidenschilling 1988; Mizuno 1989), limiting the time available for radial diffusion.

in summary, some of the open questions relevant to the evolution of the dust are:

1. What is the composition and initial size distribution of dust in accretion disks, and what is the corresponding opacity?

2. Is thermal convection the sole cause of turbulence?

3. What effect did species condensation, such as water ice, have on the opacity and subsequent evolution Of the nebula?

4. To what extent were dust particles transported radially? Was radial transport sufficient to bring inner solar system condensates to the zone of comet formation?

S. *4 Evolution of Dust Properties from Molecular Clouds to Comets*

We have seen that the composition, size, and shape of I S grains are strong] y modified within molecular clouds. Although models differ in detail, there is a general picture of silicate cores with accreted mantles in various stages of processing, from organic refractory residues to an outer layer of volatile ices. These core-mantle particles, as well as small bare silicate and carbon grains, arc agglomerated into fluffy structures. These heterogenous particles constituted the solid portion of the material from which the protosolar nebula evolved.

Current evidence tells us that comets formed cold, in the outer parts of the solar nebula where accretion shock heating and radiant heating from the protosun were minimal. in general, the relative abundances of molecular species in cornets are consistent with the inferred (observed or predicted) composition of IS dust in dense regions (e.g. Greenberg & Shalabiea 1993).

The silicate feature in several comets shows an 11.2 μm peak due to crystalline olivine, superimposed on a broad smooth feature peaking at 9.8 μm (section 4.1). The broad feature resembles that seen in both the diffuse ISM and dense clouds. With the exception of a weak signature in AFGL2591 (Aitken *et al.* 1988), the 11.2 μm olivine peak has not been detected in any protostellar source nor in the ISM. '1'bus, the cometary olivine particles most likely condensed in the hot inner solar nebula and were transported to the region of cornet formation.

T 'his raises an important issue: When considering the organic components, we often assume that the comet material is "local", i.e., not heated within the solar system. But, if there is a component of refractory silicates transported from the inner solar nebula, there may also be a higher-temperature organic component transported to the comet-forming region.

Organic material is thought to be the main reservoir of carbon in cm-nets (Greenberg & Shalabiea 1993). The dust impact experiment on the Halley probes proved that refractory organic material ("C] ION") is an important component of comet dust, These grains arc apparent] y the source of CO, H_2CO, and other gaseous species in the coma requiring a distributed source (e.g. Meier et *al.* 1993). Polymerized H_2CO, and similar long chain polymers can explain the pattern of heavy atomic mass species detected by the gas mass spectrometers on the Halley probes (Korth *et al.* 1986). Such polymers arc a product of photolysis of icy grain mantles in molecular clouds (Schutte et *al.* 1993).

The CO:H_2O abundance in comets is a strong argument that cometary ices stem directly from IS ices, not from the gas phase. In the gas phase of dense clouds, CO:H_2O is 10:1 or larger, while in the gases sublimating from comets, CO:H_2O is about 1:5 or less, a factor of 50 difference. Molecules such as H_2CO, CH_3OH, CO_2, which are present at the few percent level in comets, are UV photolysis products in IS grain mantles.

In summary, the evidence from comets and cometary IDPs is consistent with their formation primarily from IS dust similar to that seen in dense clouds, including preservation of low-temperature ices. However, some high-temperature solar system condensates may have been added during cometary formation.

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