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Astrophysical Dust Grains in Stars, the Interstellar Medium, and the Solar System

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ABSTRACT

Studies of astrophysical dust grains in circumstellar shells, the interstellar medium (ISM), and the solar system, may provide information about stellar evolution and about physical conditions in the primitive solar nebula. Infrared observations give information about the mineral composition and size distribution of the grains. Grain materials identified in sources external to the solar system include silicates, silicon carbide, amorphous carbon, and possibly hydrocarbon compounds. The nucleation and growth of astrophysical carbon grains has been documented by infrared observations of classical novae. In the solar system, dust is known to be a major constituent of comet nuclei, and infrared spectroscopy of comets during perihelion passage has shown that the ablated material contains silicates, amorphous carbon, and hydrocarbons. Cometary grains resemble extra-solar-system grains in some ways, but there is evidence for additional processing of the grain materials in comets. Comets are discussed as a possible source for zodiacal dust.

Solar system grain materials have been sampled by the collection of micrometeorites and by isolating microscopic inclusions in meteorites. Meteorite inclusions exhibit several chemical abundance anomalies that are similar to those predicted to be produced in the explosive nucleosynthesis that accompanies novae and supernovae. The possible connections between extra-solar-system astrophysical dust grains and the grains in the solar system are explored. A recent suggestion that grains are rapidly destroyed in the interstellar medium by supernova shocks is discussed. Experiments to establish the relationships between extra-solar-system astrophysical grains

and solar system grains, and between cometary dust and the zodiacal dust are suggested. Among the most promising are sample return missions and improved high-resolution infrared spectroscopic information.

THE CYCLING OF DUST IN STELLAR EVOLUTION AND THE FORMATION OF PLANETARY SYSTEMS

Small refractory dust grains are present in circumstellar shells around many different classes of stars, in the interstellar medium (ISM), and in comets and the zodiacal cloud in the solar system. The mineral composition and size distribution of the grains in all three environments have similarities, but there are also distinct differences. Condensable elements produced in stars during nucleosynthesis presumably condense into grains during the final mass-loss stages of stellar evolution in aging stars like M-type giants and supergiants (Gehrz 1989), or during nova and supernova eruptions (Clayton 1982; Gehrz 1988). These grains can be expelled into the ISM where they may be processed further by supernova shocks and in molecular clouds. The grains can eventually be incorporated into young stars and planetary systems during star formation in the clouds (Gehrz *et al.* 1984).

Dusty and rocky solids that may derive from remnants of the formative phase are present in our own solar system and around some other main-sequence stars. Grains could therefore be a significant reservoir for condensable elements, effecting the transportation of these elements from their sites of production in stars into new stellar and planetary systems.

Studies of astrophysical grains can provide significant information about stellar evolution, physical conditions in circumstellar environments, and processes that occur during star formation. In particular, grains in the solar system may contain evidence about conditions in the early solar nebula. A major issue is whether grains made by stars actually survive intact in significant quantities as constituents of mature planetary systems, or whether most of the dust we see in the ISM and the solar system represents a re-accretion of condensables following the destruction of circumstellar or interstellar grains. There is theoretical evidence that grains can be destroyed in both the ISM (Seab 1987) and during the formation of planetary systems (Boss 1988). A paucity of gas-phase condensables in the ISM (Jenkins 1987), a low input rate to the ISM of dust from evolved stars (Gehrz 1989), and evidence for a hydrocarbon component in ISM grains (Allamandola *et al.* 1987) all suggest that grains can accrete material in molecular clouds. If the grains can survive the interstellar and star formation environments intact, then studies of the elemental abundances and minerology of solar system grains may provide fundamental information about stellar nucleosynthesis and evolution. If the grains are substantially processed, or evaporate and recondense after leaving the circumstellar environment, then their chemical history may be much more difficult to evaluate, and their current composition may reflect relatively recent events. This review discusses the observed characteristics of astrophysical grains, compares the properties of grains in the solar and extra-solar environments, and suggests investigations to address the question of whether stardust is an important constituent of solar system solids.

ASTROPHYSICAL DUST GRAINS IN CIRCUMSTELLAR ENVIRONMENTS

Infrared observations made more than two decades ago provided the first convincing evidence that dust grains are present in the winds of late-type giant and supergiant stars. Most of this circumstellar dust is refractory material. Woolf and Ney (1969) were the first to recognize that silicate grains, similar in mineral composition to materials in the Earth's crust and mantle, were a major constituent of the dust in oxygen-rich stars.

Circumstellar stardust around carbon-rich stars is composed primarily of amorphous carbon and silicon carbide (Gehrz 1989). The identification of the silicate and SiC material comes from 10 and 20μm emission features caused by the Si-O/Si-C stretching and O-Si-O bending molecular vibrational modes (see Figures 1 and 2). Silicates, having the triatomic molecule SiO_2 in their structure, show both the features. The diatomic molecule SiC cannot bend, and therefore exhibits only the μm stretching feature. The 10 and 20μm emission features in stellar objects are broad and generally devoid of the structure generally diagnostic of crystaline silicate minerals like Olivine and Enstatite (Rose 1979; Campins and Tokunaga 1987). This suggests that the silicateous minerals in stardust are amorphous, and that the grains probably have a considerable spread in size distribution.

Some astrophysical sources exhibit near infrared emission or absorption features in the 3.1 to 3.4μm spectral region (see Figure 3) that have been attributed to stretching vibrations in C-H molecular bonds associated with various hydrocarbon compounds (Allamandola 1984; Sakata *et al.* 1984; Allamandola *et al.* 1987; Allen and Wickramasinghe 1987). The hydrocarbon grain materials proposed to account for these features include polycyclic aromatic hydrocarbons (PAH's), hydrogenated amorphous carbon (HAC's), and quenched carbonaceous composites (QCC's). There is evidence for the presence of hydrocarbon grains in the near infrared spectra of a handful of stellar objects (see de Muizon *et al.* 1986; Gehrz 1989).

Observations have confirmed the existence of dust in circumstellar environments other than those associated with late-type stars. Dust is known to have condensed around novae (Gehrz 1988) and probably can

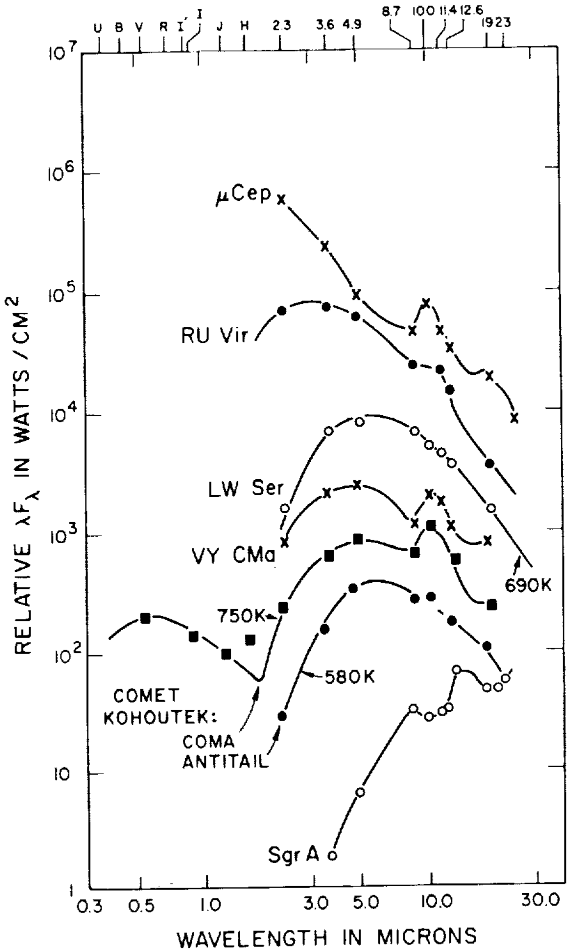

FIGURE 1 The infrared energy distributions of various objects that show emission or absorption due to small astrophysical dust grains. VY CMa and μ Cep are M supergiants (oxygen-rich stars) that have strong 10 and 20μm silicate emission features (Gehrz 1972). These same emission features appear in the comae of comets (Comet Kohoutek) where the grains are small (Ney 1974). The superheat in the coma dust continuum shows that the grains, probably amorphous carbon, producing this continuum are also small. The feature is weak in the Kouhoutek antitail because the grains are large (Ney 1974). General interstellar silicate absorption at 10 and 20μm is evident in the nonthermal spectrum of the Galactic Center source Sgr A (data from Hackwell *et al.* 1970). Carbon stars (RU Vir) often show a 11.3μm emission feature caused by SiC and a near infrared thermal continuum due to amorphous carbon (Gehrz *et al.* 1984). Novae (LW Ser) form carbon dust in their ejecta (Gehrz *et al.* 1980). The carbon produces a grey, featureless continuum from 2 to 23μm. The superficial similarities in the spectra of these objects is striking.

form in the ejecta from supernovae, though there is as yet no unambiguous observational evidence for supernova dust formation (Gehrz and Ney 1987).[1]

A small amount of dust is also present in the winds of planetary nebulae (Gehrz 1989) and Wolf-Rayet (WR) stars (Hackwell *et al.* 1979; Gehrz 1989). The Infrared Astronomical Satellite (IRAS) provided far infrared data that show evidence for the existence of faint, extended circumstellar dust shells around some main sequence (MS) stars (Aumann *et al.* 1984; Paresce and Burrows 1987). These shells, typified by those discovered around Vega (α Lyr) and β Pic, are disk-like structures believed to be fossil remnants of the star formation process. Although the material detected by IRAS around MS stars is most likely in the form of small and large grains, the presence of planets within the disks cannot be ruled out. The existing data are not spatially or spectrally detailed enough to lead to definitive conclusions about the mineral composition and size distribution of these fossil remnants of star/planetary system formation. There are large amounts of dust present in the circumstellar regions of many young stellar objects (YSO's), often confined in disk-like structures that are associated with strong bipolar outflows (Lada 1985). In the case of YSO's, it is unclear whether the dust is condensing in the wind or remains from the material involved in the collapse phase.

Most main-sequence stars and older YSO's do not have strong infrared excesses from dust shells, nor do they show evidence for visible extinction that would be associated with such shells. It is tempting to conclude that the shells in these objects have been cleared away in the early stages of stellar evolution by stellar winds, by Poynting-Robertson drag, or by the rapid formation of planets (see the contribution by Strom *et al.* in these proceedings). Rapid clearing of the circumstellar material poses a problem for the rather long time scale apparently required for the formation of giant planets (see the contribution by Stevenson in these proceedings). An alternative possibility is that dust grains grow to submillimeter or centimeter sizes (radii from 100 microns to 10 centimeters) during the contraction of the core to the Zero Age Main Sequence (ZAMS). Such grains will produce negligible extinction and thermal emission compared to an equal mass of the 0.1-10 micron grains that are believed to make up most of the material in circumstellar shells that reradiate a substantial fraction of the energy released by the central star. It can be shown that the opacity of a circumstellar shell of mass $M = N4\pi\rho a^3/3$ (where N is the number of grains in the shell, ρ is the grain density, and a is the grain radius) is

[1] SN 1987a is believed to have condensed dust grains about 400 days after its eruption. The dust formation is discussed in an analysis of recent infrared data by R.D. Gehrz and E.P. Ney (1990. Proc. Natl. Acad. Sci. 87:4354-4357).

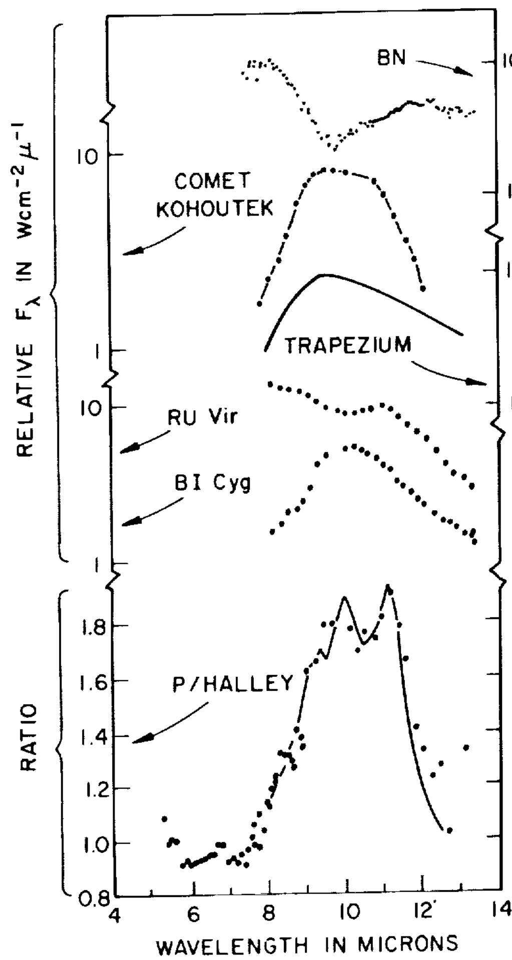

FIGURE 2 High-resolution infrared spectra of the 7-14 micron emission and absorption features of different astrophysical sources illustrating some basic differences between extra-solar-system sources and comets. The classical astrophysical 10μm silicate emission feature, typified by the Trapezium emissivity profile (Gillett *et al.* 1975) and the M-supergiant BI Cyg (Gehrz *et al.* 1984), peaks at 9.7μm. It is broad and without structure, suggesting that the grains are amorphous with a wide range of grain sizes. The feature appears in absorption in compact sources deeply embedded in molecular cloud cores such as the BN (Becklin-Neugebauer) object in Orion (Gillett *et al.* 1975). The carbon star RU Vir exhibits a classical 11.3μm SiC emission feature (Gehrz *et al.* 1984). Comet Kohoutek data are from Merrill (1974) as presented by Rose (1979). The 10μ emission feature of Kohoutec is similar to the classical astrophysical silicate feature. P/Halley's emission feature (Bregman *et al.* 1987) shows detailed structure suggesting that the grain mixture contains significant quantities of crystaline anhydrous silicate minerals. The solid line to the P/Halley data is a fit based on spectra of IDP's with Olivene and Pyroxene being the dominant components (Sandford and Walker 1985). The feature at 6.8μm may be due to carbonates or hydrocarbons.

inversely proportional to the grain radius if M is held constant. A shell of 0.1 micron grains would be reduced in opacity by a factor of 10^6 if the grains were accreted into 10 cm planetesimals while the total circumstellar dust mass remains constant. A 10 $L_\odot$ star would require the age of the solar system to clear 10 cm planetesimals from a circumstellar radius of 10 AU by Poynting-Robertson drag, and the sweeping effects of radiation pressure on 10 cm grains would be negligible. It would appear possible to postulate scenarios for the accretion of large circumstellar bodies that are consistent with both the relatively rapid disappearance of observable circumstellar infrared emission and the long time scales required for giant planet formation.

CIRCUMSTELLAR GRAIN FORMATION AND MASS LOSS

The observations described above suggest that many classes of evolved stellar objects are undergoing steady-state mass loss that injects stardust of various compositions into the interstellar medium. Gehrz (1989) has estimated the rates at which various grain materials are ejected into the ISM by different classes of stars. Stardust formation in most stars is a steady-state process, and the detailed physics of the grain formation is exceedingly difficult to resolve with current observational capabilities. Infrared studies of objects exhibiting outbursts that lead to transient episodes of dust formation, on the other hand, have revealed much about the formation of stardust and its ejection into the ISM. The long-term infrared temporal development of a single outburst is governed by the evolution of the grains in the outflow. Observations have shown that it is possible in principle to determine when and under what conditions the grains nucleate, to follow the condensation process as grains grow to large sizes, to record the conditions when grain growth ceases, and to observe behavior of the grains as the outflow carries them into the ISM.

The primary examples of transient circumstellar dust formation have been recorded in classical nova systems (Gehrz 1988) and WR Stars (Hackwell *et al.* 1979). In both cases, grains nucleate and grow on a time scale of 100 to 200 days, and the grains are carried into the ISM in the high-velocity outflow. The dust formation episodes apparently occur as frequently as every five years in WR stars and about once per 100-10,000 years in classical novae. About 10^{-6} to 10^{-5} solar masses of dust form in each episode, and the grains can grow as large as 0.1 to 0.3 microns. There is evidence that the grains formed in nova ejecta are evaporated or sputtered to much smaller sizes before they eventually reach the ISM. Novae have been observed to produce oxygen silicates, silicon carbide (SiC), amorphous carbon, and perhaps hydrocarbons (Gehrz 1988; Hyland and MacGregor 1989); WR stars apparently condense iron or amorphous carbon (Hackwell *et al.* 1979).

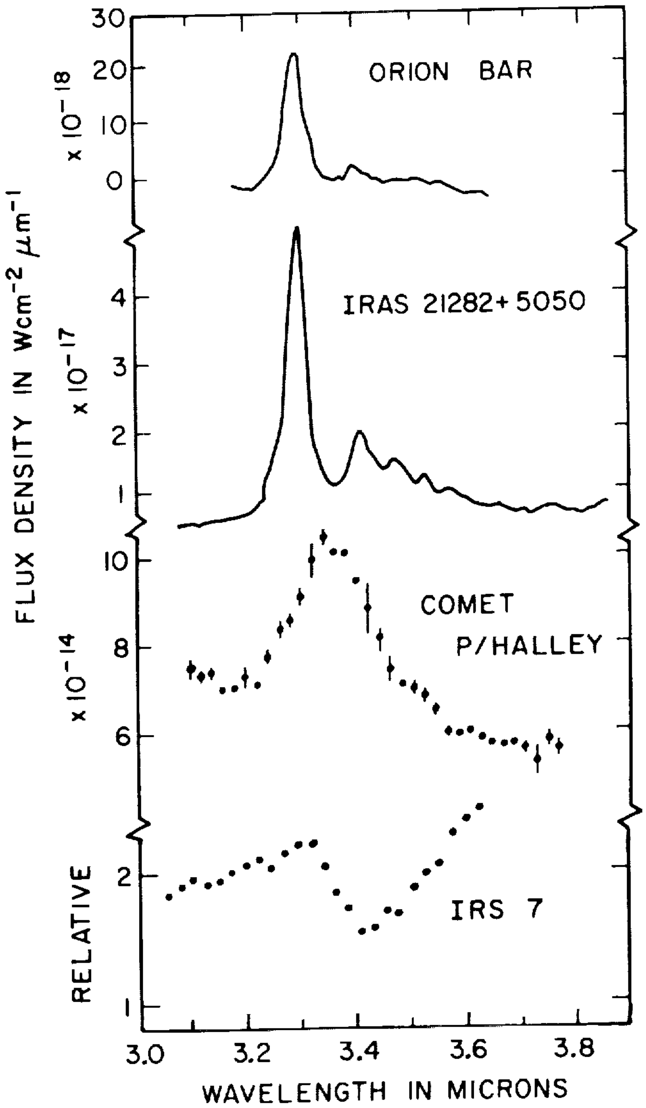

FIGURE 3 High-resolution infrared spectra of the 3.3-3.4μ hydrocarbon emission and absorption bands in three extra-solar-systems sources and Comet Halley. The Orion Bar is a shocked emission region in a molecular cloud; the Orion Bar curve is drawn after data from Bregman *et al.* (1986, in preparation) as shown in Figure 1 of Allamandola *et al.* (1987). IRAS 21282+5050 is a compact star-like object of undetermined nature (after data from de Muizon *et al.* 1986). Comet P/Halley (Knacke *et al.* 1986) has features that are broader and peak at longer wavelengths than the features of the comparison objects. Bottom curve shows a 3.5μm interstellar absorption feature in the spectrum of IRS 7, a highly reddened source near the Galactic Center (Jones *et al.* 1983).

Classical novae typify the episodic circumstellar dust formation process. Their infrared temporal development progresses in several identifiable stages. The initial eruption results from a thermonuclear runaway on the surface of a white dwarf that has been accreting matter from a companion star in a close binary system. Hot gas expelled in the explosion is initially seen as an expanding pseudophotosphere, or "fireball." Free-free and line emission are observed when the expanding fireball becomes optically thin. A dust condensation phase, characterized by rising infrared emission, occurs in many novae within 50 to 200 days following the eruption. The infrared emission continues to rise as the grains grow to a maximum radius. Grain growth is terminated by decreasing density in the expanding shell. The infrared emission then declines as the mature grains are dispersed by the outflow into the ISM. The rate of decline of the infrared radiation and the temporal development of the grain temperature suggest that the grain radius decreases either by evaporation or sputtering during their dispersal. Existing observations are consistent with the hypothesis that the nova grains could be processed to interstellar grain sizes before they reach the ISM.

Hydrocarbon molecules described above (PAH's, HAC's, QCC's) may produce some of the infrared emission features observed in planetary nebulae, comets, and molecular cloud cores (see Figure 3 and Allamandola *et al.* 1987). Although Hyland and MacGregor (1989) have reported possible hydrocarbon emission from a recent nova, and Gerbault and Goebel (1989) have argued that hydrocarbons may produce anomalous infrared emission from some carbon stars, there is currently no compelling evidence that hydrocarbon grains are an abundant constituent of the dust that is expelled into the ISM in stellar outflows (Gehrz 1989). Generally, circumstellar hydrocarbon emission is observed only in sources with high-excitation nebular conditions (Gehrz 1989). There is circumstantial evidence that grains condensed in the ejecta of novae, supernovae, and WR stars may contain chemical abundance anomalies similar to those in solar system meteorite inclusions (see below and Clayton 1982; Truran 1985; Gehrz 1988).

INTERSTELLAR DUST GRAINS

Hackwell *et al.* (1970) showed that the same 10- and 20-meter silicate features responsible for emission in M-stars were present in absorption in the infrared spectrum of the non-thermal Galactic Center source Sgr A. They concluded that the absorption was caused by interstellar silicate grains in the general ISM and that the grains are similar to those seen in M-stars. Interstellar silicate absorption has since been confirmed for a variety of other objects that are obscured by either interstellar dust or cold dust in molecular clouds (see, for example, the BN object in Figure 2 and the other objects embedded in compact HII regions discussed by Gillett *et al.* 1975).

There is roughly 0.04 mag of silicate absorption per magnitude of visual extinction to Sgr A. Observations of stellar sources with interstellar silicate absorption along other lines of sight in the Galaxy yield similar results.

Continuum reddening by interstellar dust in the general ISM has been measured by a number of investigators who compared optical/infrared colors of reddened luminous stars with the intrinsic colors exhibited by their unreddened counterparts (Sneden *et al.* 1978; Rieke and Lebofsky 1985). Interstellar dust also polarizes starlight (Serkowski *et al.* 1975). An estimate of the grain size distribution for the grains causing this so-called "general" interstellar extinction can be made given the wavelength dependence of the reddening and polarization curves. The same reddening and polarization laws appear to hold in all directions in the galaxy that are not selectively affected by extinction by dense molecular clouds. The reddening and polarization curves observed for stars deeply embedded in dark and bright molecular clouds lead to the conclusion that the grains in clouds are substantially larger than those causing the general interstellar extinction (Breger *et al.* 1981).

The shape of the general interstellar extinction curve as determined by optical/infrared measurements is consistent with the assumption that the ISM contains carbon grains of very small radii (0.01-0.03μm) and a silicate grain component (Mathis *et al.* 1977; Willner 1984; Draine 1985). Both components are also observed in emission in dense molecular cloud cores where the dust is heated by radiation from embedded luminous young stars (Gehrz *et al.* 1984). The ISM dust in dense clouds contains a probable hydrocarbon grain component that causes the 3.2-3.4μm emission features (see Figure 3), and several other "unidentified" infrared emission features that are seen in the 6-14μm thermal infrared spectra of some HII regions, molecular cloud cores, and young stellar objects (Allamandola 1984; Allamandola *et al.* 1987). Jones *et al.* (1983) showed that a 3.4μm C-H stretch absorption feature is present in the spectrum of the highly reddened source IRS7 towards the Galactic Center (see Figure 3). SiC has not been observed in either the general extinction or in the extinction/emission by molecular cloud grains, but its presence may be obscured by the strong silicate features.

At least some of the dust present in the ISM must be stardust produced by the processes described above. Gehrz (1989) has reviewed the probable sources for the production of the dust that is observed to permeate the ISM. These include condensation in winds of evolved stars, condensation in ejecta from nova and supernovae, and accretion in dark clouds. Most of the silicates come from M stars and radio luminous OH/IR (RLOH/IR) stars; carbon stars produce the carbon and SiC. Some stars, novae, and supernovae may eject dust with chemical anomalies. Since there is apparently not a substantial stellar source of hydrocarbon grains, the ISM hydrocarbon component may be produced during grain processing or growth in molecular clouds. The observation that there are large grains in molecular clouds provides additional evidence that grains can grow efficiently in these environments.

COMET DUST AND THE ZODIACAL CLOUD

The thermal infrared energy distributions of the comae and dust tails of most comets (see Figures 1 and 2) show the characteristic near infrared continuum dust emission that is probably caused by small iron or carbon grains, and prominent 10 and 20m emission features characteristic of silicate grains (Ney 1974; Gehrz and Ney 1986). The cometary silicate features, first discovered in Comet Bennett by Maas *et al.* (1970), suggest that comets contain silicate materials similar to those observed in the circumstellar shells of stars and in the ISM. Determinations of the composition of Halley's coma grains by the Giotto PIA/PUMA mass spectrometers appear to confirm the silicate grain hypothesis (Kissell *et al.* 1986). There are some basic differences however, between the cometary 10m emission features and their stellar/interstellar counterparts (see Figure 2). As discussed above, the latter are broad and structureless suggesting a range of sizes and an amorphous grain structure. The 10μm feature in P/Halley, on the other hand, shows definite structure that suggests the presence of a grain mixture containing 90% crystalline silicates (55% olivines, 35% pyroxene) and only 10% lattice-layer silicates (Sandford and Walker 1985; Sandford 1987; Gehrz and Hanner 1987). This observation would imply that the grains in some comets may have undergone considerable high-temperature processing compared to extra-solar-system grains. Some pristine comets, like Kohoutek, show a 10m feature more like the stellar feature (see Figure 2 and Rose 1979). In the case of Kohoutek, the model fits indicate that the mineral composition is almost entirely low-temperature hydrated amorphous silicates (Rose 1979; Campins and Tokunaga 1987; Hanner and Gehrz 1987; Brownlee 1987; and Sanford 1987).

The 3 to 8μm thermal continuum radiation in the comae and Type II dust tails of most comets are often hotter than the blackbody temperature for the comet's heliocentric distance (Ney 1982). This "superheat" suggests that the grains are smaller than about 1 micron in radius. ISM grains may be 10 to 100 times smaller than this. The antitail of Kohoutek was cold with only weak silicate emission showing that comets also have much larger grains frozen in their nuclei (Ney 1974).

The 3.3-3.4μm feature (see Figure 3) in P/Halley suggests the presence of hydrocarbon grains in the ablated material. It is obvious that the Halley emission feature differs substantially both in width and effective wavelength from the 3.3-3.4μm emission seen in other astrophysical sources. The implication is that the material in P/Halley has been processed in some way compared with the material observed in extra-solar-system objects.

Comets are presumably a Rosetta Stone for the formation of the solar system because the contents of their nuclei were frozen in the very early stages of the accretion of the solar nebula. The grains contained therein may be indicative of interstellar material in the primitive solar system, or may represent material processed significantly during the early collapse of the solar system. These materials are ablated from comet nuclei during perihelion passage. Cometary particles injected into the interplanetary medium by ablation probably produce the shower meteors and the zodiacal cloud. Studies of zodiacal dust particles may therefore provide important information about the properties of cometary dust grains. No cometary or zodiacal particles have yet been collected *in situ*. However, Brownlee (1978) and his recent collaborators have collected grains believed to be interplanetary dust particles (IDP's) from the stratosphere, on the Greenland glaciers, and off the ocean floor. These particles yield infrared absorption spectra showing that they are composed primarily of crystalline pyroxene and olivines, and layer-lattice silicates (Sandford and Walker 1985). Composite spectra modeled by combinations of these particles have been shown to match the Halley and Kohoutek data reasonably well (Sandford and Walker 1985; Sandford 1987). There is no evidence for 3.4μm hydrocarbon features in the laboratory spectra of IDP's, but there are spectral peculiarities that are associated with carbonaceous minerals. Walker (1987) has analyzed the minerology of IDP's and concludes that they are comprised largely of materials that were formed in the solar system and contain only a small fraction of ISM material in the form of very small grains. The comparisons between IDP's and comets are, of course, only circumstantial at present. It is therefore crucial to contemplate experiments to collect zodiacal particles and cometary grains to establish the connections between zodiacal, cometary, and interstellar/circumstellar particles.

THE SURVIVAL OF DUST GRAINS DURING STELLAR EVOLUTION

An intriguing question is whether significant numbers of stardust grains can survive from the time that they condense in circumstellar outflows until they are accreted into the cold solid bodies in primitive planetary systems. While there is evidence that grains are rapidly destroyed in the ISM by supernova shocks (Seab 1987) and are heated above the melting point in the nebular phases of collapsing stellar systems (Boss 1988), there is equally compelling evidence for the existence of solar-system grains that are probably unaltered today from when they condensed long ago in circumstellar outflows (Clayton 1982). If stardust cannot survive long outside the circumstellar environment, then most of the grains in evolved planetary systems must be those that grew in ISM molecular clouds and/or those that condensed in the collapsing stellar systems.

It is difficult to escape the conclusion that grains can be destroyed in the ISM. Seab (1987) has reviewed the possibility that ISM grains are rapidly destroyed by supernova shock waves on very short time scales (1.7-5 $\times$ 10^7 yrs). He notes however, that the extreme depletion of refractory grain materials in the ISM is difficult to reconcile with the destruction hypothesis. Assuming the gas mass in the Galactic ISM is 5×10^9 $M_\odot$ with a gas to dust ratio of 100/1, shocks will process 10-30 $M_\odot$ yr^{-1} in gas and destroy 0.1-0.3 $M_\odot$ yr^{-1} in dust.

Despite the rapid destruction that may befall ISM grains, it appears likely that they can reform and grow to large sizes in molecular clouds and star formation regions. Gehrz (1989) examined the galactic dust ecology by comparing circumstellar dust injection with depletion by star formation and supernova shocks and found that dust grains may be produced by accretion in molecular clouds at one to five times the circumstellar production rate. There is currently no observational evidence for a substantial stellar source of hydrocarbon grains. If this is the case, then the production of hydrocarbon grains and hydrocarbon mantles on stardust may be primarily an ISM process. Seab (1987) has predicted rapid accretion rates for grains in molecular clouds ($\approx 10^6 - 10^7$ years) which implies that such clouds could be efficient sources for the production and/or growth of dust in the ISM. Depletions in the ISM of heavy elements associated with dust (Jenkins 1987) are a strong indication that any gas-phase heavy elements ejected from stars are efficiently condensed onto ISM dust grains. Since early-type stars (WR stars, Of stars), and supernovae can eject a significant amount of gas-phase condensable matter on a galactic scale, it seems highly likely that these materials must be incorporated into dust in the ISM itself.

There is substantial evidence that there were high temperatures (1700-2000K) in the early solar nebula within a few AU of the sun (Boss 1988) so that most small refractory grains in this region would have melted or vaporized. On the other hand, microscopic inclusions in solar system meteorites exhibit abundance anomalies that may have been produced by the condensation of grain materials in the immediate vicinity of sources of explosive nucleosynthesis such as novae or supernovae (Clayton 1982). For example, ^{22}Ne can be made by the reaction $^{22}Na(\beta^{+\nu})^{22}Ne$ which has a half-life of only 2.7 years, so that ^{22}Ne now found in meteorite inclusions (the so-called Ne-E anomalie) must have been frozen into grains shortly after the production of ^{22}Na in a nova eruption (Truran 1985). Another anomaly seen in meteorite inclusions that can be produced in nova grains is excess ^{26}Mg from $^{26}Al(\beta^{+\nu})^{26}Mg$ which has a half-life of 7.3×10^5 years. Infrared observations have now revealed several novae in which forbidden fine structure line emission has provided evidence for chemical abundance anomalies that would be associated with the production of ^{22}Na and ^{26}Al (Gehrz 1988). Xe can be produced by a modified r-process in nucleosynthesis supernovae and trapped in grains that condense in the ejecta (Black 1975). Some of these anomalies also imply that the grains survived intact from their sites of circumstellar condensation until their accretion into the body of the meteorite. High-temperature processing might be expected to drive off volatiles such as ^{22}Ne and Xe which are highly overabundant in some inclusions.

ESTABLISHING CONNECTIONS BETWEEN STARDUST AND DUST IN THE SOLAR SYSTEM

The investigation of the properties of astrophysical dust grains is an area that can benefit from studies that use the techniques of both astrophysics and planetary science. It is now possible to conduct both remote sensing and *in situ* experiments to determine with certainty the mineral composition and size distribution of the dust in the solar system. The Vega and Giotto flybys of Comet P/Halley produced some tantalizing results that demand confirmation. A sample return mission to a comet or asteroid is of the highest priority. Any mission that returns a package to Earth after a substantial voyage through the solar system should contain experiments to collect interplanetary dust particles. It will be important to establish whether IDP's that are collected from space resemble those collected on the Earth and whether they have chemical anomalies that are similar to those seen in meteorite inclusions. Examples of missions now planned that could be modified to include IDP dust collection are Comet Rendezvous and Asteroid Flyby (CRAF) and the MARS SAMPLE RETURN missions. The mineral composition of the zodiacal cloud remains uncertain. Infrared satellite experiments to measure the spectrum of the cloud can provide significant diagnostic information. Near infrared reflectance spectroscopy can reveal the presence, mineral composition, and size distribution of various types of silicate grains. These features have already been observed in the spectra of asteroids. Emission spectroscopy can determine whether silicates and silicon carbide are present. The contrast of the 10-20μm emission features are related to the size distribution (Rose 1979). Ground-based studies of the mineralogy of stardust and solar system dust also require high signal to noise high-resolution spectroscopy of the emission features shown in Figures 1 and 3 in a wide variety of sources. New improvements in infrared area detectors should make achievement of this objective realistic within the coming decade.

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