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CIRCUMSTELLAR DUST

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The presence of dust in the general interstellar medium is inferred from the extinction, polarization, and scattering of starlight; the presence of dark nebulae; interstellar depletions; the observed infrared emission around certain stars and various types of interstellar clouds. Interstellar grains are subject to various destruction mechanisms that reduce their size or even completely destroy them (e.g. Seab et al, this volume). A continuous source of newly-formed dust must therefore be present for dust to exist in the various phases of the interstellar medium (ISM).

This working group has the following goals: 1) review the evidences for the formation of dust in the various sources; 2) examine the clues to the nature and composition of the dust; 3) review the status of grain formation theories; 4) examine any evidence for the processing of the dust prior to its injection into the interstellar medium; and 5) estimate the relative contribution of the various sources to the interstellar dust population.

Sources considered in this report are: cool giant and supergiant stars, planetary nebulae, hot stars, evolved stars, novae, supernovae, and protostars. A brief review on observational aspects of circumstellar dust, and on the formation of circumstellar grains is given, respectively, by Jura and by Draine in this volume.

1. EVIDENCE FOR DUST FORMATION

The presence of dust in circumstellar shells around **cool evolved stars** is inferred from the infrared (IR) excess above the underlying stellar continuum or free-free emission, from the polarization of starlight, and from the presence of reflection nebulae surrounding the star. The IR excesses are apparent at wavelengths above 5 microns. They appear either as a continuum that exhibits a shallower falloff with increasing wavelength compared to the underlying stellar emission, or exhibit characteristic dust emission features.

In **planetary nebulae** the presence of dust is also inferred from the extinction and scattering of the stellar UV and optical emission. However, an unresolved issue is the phase in the evolution of the star during which the dust actually formed. The dust could have formed during the red giant phase, and been accumulated in a shell during the formation of the planetary nebula. Alternatively, the dust could have formed during the planetary ejection phase.

The presence of dust around **novae** is inferred from the evolution of their radiative output at the various wavelengths. A few months after the explosion, the nova light curve may exhibit a dramatic rise in the infrared which is concurrent with a rapid drop in the UV-visual (e.g. Gehrz et al., 1980 and references therein). The appearance of the infrared excess is usually interpreted as evidence for the formation of dust in the expanding novae ejecta (e.g. Clayton and Wickramasinghe, 1976). The appearance of the dust in the expanding shell is then also the cause for the drop in the observed UV output from the star. A different explanation was offered by Bode and Evans (1980a). They suggested that the dust around some novae was not formed during the nova event but during an earlier phase in the evolution of the progenitor star. The observed IR excess in their model therefore represents the reprocessing of the UV-visual output of the star by the preexisting circumstellar dust shell. The concurrent drop in the UV is more difficult to explain in their model, and is attributed to an increase in the effective temperature of the nova that is associated with its decreasing photospheric radius (Bath and Shaviv, 1976).

That dust formation may take place in **supernovae (SN)** is inferred from the presence of isotopic anomalies in meteorites (see D. D. Clayton, et al. in this volume). In the absence of an underlying source of UV emission, which provides the heating of the dust in novae, it may be impossible to obtain evidence for the formation of dust in the expanding SN ejecta from the evolution of the SN light curve. The excess of IR emission detected in three recent Type II supernovae (Merrill, 1979; Dwek et al., 1983; Graham et al., 1984) represents in all three cases the UV-visual outburst of the star reprocessed by circumstellar dust that presumably formed during the red giant phase of its evolution (Bode and Evans, 1980b; Dwek, 1983). Of the three supernovae only SN 1980k was also consistent with the interpretation that dust formed in the SN ejecta (Dwek et al., 1983). Direct evidence for the existence of supernova condensates can be obtained by infrared observations of young, relatively unmixed supernova remnants (Dwek and Werner, 1981). Two such candidates are the Crab Nebula and the Cas A remnant, however, so far neither remnant shows any conclusive evidence that the observed dust is of supernova origin (Marsden et al., 1984, and Dwek et al. in preparation).

Protostars are observed to be embedded in cocoons of dust and were suggested by Field (1974) as major sources of interstellar dust. The observed circumstellar dust may, however, be preexisting dust from the protostellar environment out of which the star formed.

Evolved stars like R Coronae Borealis are extremely carbon-rich objects ($C/H \gg 1$) which periodically fade up to eight magnitudes in the visual. Typically after several months, they return to normal (Payne-Gaposchkin, 1963; Alexander et al., 1972). Subsequent to the discovery of an IR excess around R Coronae Borealis (RCB) (Stein et al., 1969) it has been generally accepted that dust is always present around RCB type stars. The fading of the star is attributed to the ejection of a cloud of carbon grains along our line of sight (O'Keefe, 1939; Forrest et al., 1972). UV observations of the star, and the derived UV extinction curves are consistent with that hypothesis (Hecht et al., 1984).

2. DUST COMPOSITION

Stars with circumstellar dust shells can be grouped into two main classes based on their photospheric abundances: those in which oxygen is more abundant than carbon ($C/O<1$), and those for which $C/O>1$. The dust type in the circumstellar shell seems well correlated with these two classes: silicate dust with oxygen-rich stars, and carbonaceous and SiC particles with carbon-rich stars.

The presence of **silicates** in oxygen-rich stars is inferred from the 9.7 and 18 micron emission features (e.g. Aitken, 1981), and the featureless infrared spectrum observed in carbon stars and planetary nebulae (Mathis, 1978) is usually attributed to crystalline graphite. Draine (1984) predicted that crystalline graphite should have a resonance feature at 11.52 microns which has not yet been detected, and this may suggest that circumstellar carbon is instead amorphous. **SiC** has a broad emission feature extending from 10.5 to 13 microns which has been observed in circumstellar shells around carbon stars and some planetary nebulae (see review by Aitken, 1981). Based on cosmic abundances, it is expected that less than 10 percent of the dust around carbon-rich stars will be SiC. Therefore, SiC will be a minor contributor to the interstellar visual and UV extinction (Mathis, Rumpl, and Nordsieck, 1977). A broad 25-30 micron feature, seen in carbon stars and in carbon-rich planetary nebulae (Goebel and Moseley, 1985; Forrest, Houck, and McCarthy, 1981) was suggested by them to be a resonance feature in solid **MgS**. The feature is absent in planetary nebulae with high C/O ratios, suggesting that most of the sulphur in that case is locked up in CS.

A few oxygen-rich stars show absorption features at 3.1 microns and 6.0 microns (Soifer et al., 1981), which is characteristic of water ice at temperatures significantly lower than 150 K. These observations suggest that $\mathbf{H_2O}$ can condense out from the gas at sufficiently large distances from the star (see Jura, this volume). Additional evidence for the presence of circumstellar ice is suggested by the UV observations of HD 44179 (Sitko, Savage, and Mead, 1981), the illumination source for the Red Rectangle Nebula. The 1600 A absorption feature in the spectrum has been interpreted by Hecht and Nuth (1982) as evidence for the presence of water ice in the circumstellar shell of that star.

A variety of objects exhibit a series of "unidentified" infrared emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 microns (see review paper by Aitken, 1981). Recently, Leger and Puget (1984) suggested that these features arise from very small (50 atoms) hydrogenated carbon "grains", that are radiatively excited by the stellar UV radiation. **Polycyclic aromatic hydrocarbons** (PAH's) appear the most promising carriers of these features; however, the exact nature of the exitation mechanism is still controversial (Allamandola, Tielens, and Barker, 1985).

The presence of various elements and their isotopic composition in circumstellar dust grains can only be confirmed from the study of meteorites. Abundance anomalies in these objects suggest that volatile s-process elements, and short-lived radioactivities were trapped in circumstellar grains during the condensation process (see Clayton et al., this volume). The presence of these volatile elements in the grains provide a challenge for anyone attempting to model the condensation process in circumstellar shells.

The crystal structure of the emitting dust can affect the shape of dust emission features as well as the long wavelength behavior of the dust emissivity. This effect is most obvious in the comparison of the absorption efficiency of graphite particles (e.g. Draine and Lee, 1984) with that of amorphous carbon (e.g. Koike, Hasegawa, and Manabe, 1980). For silicates and other grain materials the differences may be more subtle. The shape of the 9.7 micron feature in circumstellar shells which is reasonably well fit by that of amorphous silicates (Papoular and Pegourie, 1983) appears different in red giant shells compared to the Trapezium (see Forrest, McCarthy, and Houck, 1979 and references therein), suggesting a different crystal structure in these regions. The significance of the difference is currently unclear, since uncertainties in the subtraction of the underlying continuum may be larger than the difference in the spectra. Additional information on the crystalline structure of grains may be inferred from the far-infrared behavior of their emissivity. An inverse square wavelength dependence is expected for crystalline particles. Recent observations (e.g. Sopka et al., 1985) suggest that the far-infrared drop in absorption efficiency of silicate or carbon grains appears to follow a wavelength $^{-1}$, or wavelength $^{-1.5}$ behavior, suggesting that these grains are amorphous. However, a distribution of grain temperatures will also have the effect of producing a flatter spectrum from an originally steeper one. More detailed observations are needed to distinguish between these two possibilities.

Additional evidence that circumstellar carbon may be amorphous, rather than crystalline graphite, is suggested by the 2400-2500 A bump in the UV extinction curves toward R Coronae Borealis stars. These stars are carbon-rich and hydrogen-poor with C/H ratios of about 100, in which graphite rather than hydrocarbons should be very stable. However, an analysis of the extinction curve (Hecht et al., 1984) showed that the feature is consistent with the presence of glassy or amorphous carbon around these stars.

3. DUST FORMATION

Although the growth of interstellar dust grains may take place in the interstellar medium (see Snow this volume) the cores of these grains are probably formed in the various sources considered in section 1. Jura (this volume) summarized radio and infrared observations of cool giant stars that can provide observational constraints on theories for dust formation in the outflowing gas. These constraints include the physical properties of the gas, and the size and composition of the dust in the outflow. A summary of how these observational constraints mesh with current theories of circumstellar dust formation was presented by Draine (this volume).

The nucleation theory which is used to describe the formation and growth of particles in astrophysical environments makes a number of simplifying assumptions which may not be valid in circumstellar flows. These assumptions are: 1) that the vibrational temperature of the clusters and the kinetic temperature of the gas are the same; 2) that the chemical distinction between the various refractory gas phase constituents can be overlooked; 3) that free energies for "critical" cluster sizes can be estimated using their bulk properties; and finally 4) that the sticking efficiency of a particle is not affected by the latent heat released by the formation of the chemical bond at the grain surface.

These assumptions are still controversial, and there is evidence that some of them are incorrect in real astrophysical environments or under laboratory conditions (Nuth and Donn, 1981; Stephens and Bauer, 1981; Donn and Nuth, 1985). Well outside the stellar photosphere the molecular vibrational temperatures drop below the kinetic temperature of the ambient gas. This disequilibrium reduces the validity of condensation calculations. More specifically, the reduced vibrational temperature will contribute to the stability of clusters and may be a key factor in the onset of the nucleation process

(Nuth et al., 1985). Another problem encountered in real astronomical environments is that the relevant collisional timescales may be longer than the dynamical timescale of the system. This point was illustrated by Scalo and Slavsky (1980), who showed that the final products of the chemical reactions between major constituents of expanding circumstellar shells may be controlled by the reaction kinetics in the outflow. Isotopic anomalies found in meteorites suggest the inclusion of volatile elements in the dust that formed around red giant stars. Nucleation theory has to include the possibility of trapping volatile elements in the condensation process (Kothari et al., 1979). In addition to simplifications in the nucleation theory, models for the formation of circumstellar dust may have considerably simplified the physical conditions of the gas in the flow.

The complexity of the actual process of circumstellar dust formation can be illustrated by applying the theory to a well observed object. The application of classical nucleation theory to circumstellar gas flows yields the point in the flow beyond which these clusters become stable, and the growth and final size of the dust particles.

Infrared photometric data of Alpha Orionis (summarized by Jura in this volume) suggests that silicate dust (observed by its 9.7 micron emission feature) is formed and detectable outside of 10-100 stellar radii (10^{14}-10^{15} cm linear dimension). The density in a spherically symmetric outflow decreases with distance from the star. Consequently, if dust formation is defered to a distance of 10-20 stellar radii, the resulting grain size is much smaller than that inferred from observations (see Draine in this volume). These problems indicate that the flow around the star is significantly more complex than assumed in the calculations. It is possible that regions interior to 10-20 R_*, which do not clearly contain the "9.7 micron dust feature", may be comprised of dust progenitors (clusters) and molecular masers that reside in cool clumps ($T<1000K$; $n<10^{10}$ cm^{-3}) which in turn are embedded in a warm, chromospheric medium (T near $10^4 K$; n approximately 10^8 cm^{-3}). A condensation instability could produce these conditions near the star (see Stencel, 1985; also this volume). Such instability could also explain the presence of dust around hot Wolf-Rayet stars that exhibit rapidly moving (3000 km/sec) outflows, or around high temperature (5000 K) R Corona Borealis stars.

In contrast to cool stars which may produce dust continuously in their outflow, novae only produce dust during sporadic outbursts. Dust formation seems, however, to be inhibited in "fast" novae, so called because they exhibit a rapid drop in their UV-visual output (e.g. Gehrz et al., 1980). Comparison between the various type novae may therefore provide the opportunity to examine the physical parameters that can facilitate (or inhibit) the formation of dust in their ejecta (Gallagher, 1977).

So far, dust has not been observed in supernova ejecta. However, it is expected that the dust formation process in these objects may be significantly different from that occuring around stars or novae. In the case of Type II supernovae, the collapse of the central core of the progenitor star leaves no underlying source of radiation so that the formation of the dust in the ejecta may be regulated by collisional, rather than radiative, processes. Furthermore, observations of Cas A and the Crab Nebula show that supernovae ejecta are inhomogeneous, with significant abundance variations between the clumps. The resulting condensation sequence and dust composition may therefore be quite different from those calculated for a uniformly expanding gas (see Clayton et al., this volume). The enhanced density in the clumps may facilitate the condensation process, and shield the newly-formed grains from reverse shocks that arise from the deceleration of the remnant.

4. PROCESSING OF THE DUST

After their formation and prior to their injection into the interstellar medium the newly-formed dust particles may be subject to various physical conditions that can reprocess them. Reheating of the dust particles can change their crystalline structure; accretion in the flow, various surface reactions, or UV processing can alter their composition; and collisions among themselves and with the ambient gas can alter their size distribution or completely destroy them.

Variations in grain composition, size, and morphology are reflected by changes in the central wavelength, strength, and shape of their characteristic infrared bands. For example, the emission peaks of crystalline silicates differ in wavelength and shape from the emission bands of amorphous silicates of the same composition (Stephens and Russell, 1979). Furthermore, the 8-25 micron spectrum of various laboratory-produced amorphous and partially crystallized silicates show, in addition to the well known 10 and 20 micron bands, weak features which may correspond to weak structures present in the infrared spectra of oxygen-rich stars (Nuth and Donn, 1982).

Evidence for changes in the grain size distribution around R Coronae Borealis stars was presented by Hecht et al. (1984). From the fading of the visual output they proposed that after formation the grains grow to approximately 0.1 micron. Subsequent collisions result in a MRN power-law distribution of sizes ranging from 0.005 to 0.060 microns.

Graphite particles can react with atomic or ionized hydrogen in the vicinity of HII regions if their temperature is above a critical temperature of about 110 K. Barlow (1983) proposed that chemical sputtering of carbon grains can form surface hydrocarbon complexes which may be responsible for the observed "unidentified" infrared emission features. UV irradiation can lead to similar results. The observations of these features on the boundary of HII regions and in planetary nebulae may therefore be evidence for radiative or collisional processes on the surface of carbon grains.

5. RELATIVE CONTRIBUTION TO THE ISM

The relative contribution of the various sources to the interstellar dust population is of considerable interest because of the different abundance peculiarities that can be locked in the dust during the condensation process. For example, silicates that formed in supernova ejecta will contain pure ^{16}O, and were suggested as the source of abundance anomalies in the meteorites. The relative contribution of each source to the interstellar dust population depends on the total amount of mass returned from that source to the ISM, on the fraction of condensible elements in the ejecta, and on the efficiency with which these elements condense out of the gas phase.

The contribution of **Red Giant stars** to the interstellar dust population is perhaps the least uncertain. In red giant winds it is possible to derive the mass loss rate from the star. If the circumstellar gas is ionized the mass loss rate can be derived from the radio free-free emission. If the hydrogen in the flow is molecular then the mass loss rate can be derived from radio observations of minor constituents such as CO. Major uncertainties in these derivations are the CO/H_2 abundance, and the distance to the star. Total mass loss rates integrated over the galaxy are found to be about 0.3 M_{sun}/yr with equal contribution from O- and C-rich stars (Knapp and Morris, 1985). Adopting a gas-to-dust mass ratio of 100 in the flow, the galactic contribution to the interstellar dust population from red giant winds is approximately $3x10^{-3}$ M_{sun}/yr. The mass of dust in the wind can also be derived directly from infrared observations. Major uncertainties in this method are the infrared properties of the dust, and the dust temperature profile from the star.

Supernovae and novae. The contribution from these sources is less certain than the contribution from red giants. If the infrared echo detected from SN 1980k is due to dust that formed in the supernova ejecta (Dwek et al., 1983) then the total amount of dust produced in that event was about $10^{-5}M_{sun}$, which makes it a neglible contributor to the interstellar dust population. IRAS observations of the Crab Nebula (Marsden et al., 1984) show that the IR excess above the radio synchrotron emission from the nebula is very small. The excess translates into a dust mass of $(5-30)x10^{-3}M_{sun}$ in the nebula which is also too small to be significant on a galactic scale. IRAS observations of the supernova remnant of Cas A show a large infrared excess above the free-free continuum. A preliminary analysis of these observations (Dwek et al., in preparation) suggests that the mass of the emitting dust is between 0.1 and 0.6 M_{sun}. Adopting an average value in that range, and a frequency of "Cas A type" supernovae of 0.01/yr gives a total galactic dust production rate of $3x10^{-3}M_{sun}$/yr, comparable to the contribution from red giant winds.

The most convincing evidence that the sudden rise in the infrared emission observed in novae is due to dust formation is the concurrent drop in the UV output from the star. The mass of dust produced in a nova event can range from 10^{-4} to 10^{-5} M_{sun}, which for a frequency of 40 events a year gives a contribution of $(4-40)x10^{-4} M_{sun}/yr$ over the galaxy (e.g. Dwek and Scalo, 1980).

Planetary nebulae and protostars. Based on infrared photometric observations of a large number of planetary nebulae Cohen and Barlow (1974) concluded that these objects are dust deficient, i.e. the dust-to-gas mass ratio in planetary nebulae is smaller than its cosmic value of 0.01. An estimate the mass of the dust requires a detailed knowledge of the composition and size distribution of the emitting particles, since these properties determine the dust temperature in a given radiation field. Based on far-infrared observations of a number of planetary nebulae Moseley (1980) concluded that their dust-to-gas mass ratio is not significantly different from that of the ISM. The gas contribution from planetary nebulae to the ISM is about $4x10^{-2}$ M_{sun}/yr (Dwek and Scalo, 1980), which for a cosmic dust-to-gas mass ratio gives an upper limit to the galactic dust contribution of $4x10^{-4} M_{sun}/yr$.

The contribution of protostars to the interstellar dust population is hard to estimate. Protostars are observed to be enshrouded in cocoons of dust. The major uncertainty is the fraction of the dust that existed prior to the formation of the star. Assuming that half of the condensible elements in the protostellar nebulae existed in the gas phase Dwek and Scalo (1980) estimated the dust contribution of protostars to be $<3x10^{-4} M_{sun}/yr$.

Hot stars and evolved objects. Infrared excesses that can be attributed to circumstellar dust were only observed in Wolf-Rayet stars of type WC9 and some WC8's. Since these stars and other evolved objects are rare their contribution to the interstellar dust is not expected to be significant. Abbott (1982) estimated the gas mass loss rate from hot stars to be $0.03 M_{sun}/yr$, giving a dust production rate $<3x10^{-4} M_{sun}/yr$.

6. PROSPECTS FOR FUTURE RESEARCH

A significant amount of observational, experimental, and theoretical work is still needed to resolve the various issues reviewed by this working group. The role of certain astronomical objects as dust sources is not yet resolved, and their contribution to the interstellar dust population is uncertain. The crystalline structure of the newly-formed dust is still subject to interpretations, and the degree of reprocessing in the circumstellar environment unclear. The identification of the carriers of the "unidentified" emission bands still needs to be firmly established, and details of the emission mechanism still need to be worked out. Details of the nucleation process are lacking, and we are ignorant about the astrophysical conditions in the condensation sites. More specifically, the following list of objectives may help resolve some of the issues mentioned above.

Extensive mapping of the infrared emission around planetary nebulae will establish the location of the dust with respect to the HII region and may resolve the question of whether the observed dust was preexisting material that was merely "pushed" out during the planetary ejection phase or whether it formed in the planetary nebula.

Supernovae may contribute as much dust to the interstellar medium as giant and supergiant stars. However the presence of dust in supernova ejecta has not yet been established. IRAS follow-up observations with high spatial resolution of young, unmixed, "Cas A type" supernova remnants will be an important step in that direction. High spectral resolution observations are needed to estimate the contribution of infrared emission lines to the observations. Coordinated infrared and optical searches for Type II supernovae are important if one hopes to observe the dust during its formation phase.

Spatial imaging, especially within a few tens of stellar radii, and the determination of dust and molecular abundances with distance (radial and azimuthal) is a useful observation to pursue. An evolutionary sequence ("atoms" to molecules to clusters to pregrains to grains) with distance from the star will yield valuable information on the development of grains in the outflow.

Condensation experiments are needed to examine the validity of classical nucleation theory in astrophysical environments. Any alternative theory will have to include the possibility of trapping volatile elements in the condensing particles. A full kinetic nucleation model will require detailed transition rates between the various states of the system.

More observations are needed to characterize the physical conditions in the various condensation sites. The implication of these conditions for the nucleation process need to be examined. For example, many red giants and related stars are observed to pulsate and create slow shocks and density inhomogeneities in the outflow. The role of these shocks and inhomogeneities (if they persist in the flow) in the nucleation process is unclear.

Observations capable of detecting spatial or temporal variations in grain properties by means of variations in their spectral properties are critical to elucidating processing of circumstellar grains. Changes in the crystal structure of grains due to processing in a circumstellar environment may be monitored by narrow spectral band mapping of the circumstellar region at wavelengths centered on the amorphous and crystalline silicate bands. Changes in metal to silicon ratio of amorphous silicates introduces small spectral shifts which may be monitored using this technique.

Grain destruction in the ISM is predicted to be so efficient that it becomes difficult to account for the observed abundance of refractory grains in the ISM, or to account for the preservation of isotopic anomalies in the meteorites. The contribution of the various sources to the production of interstellar grains needs to be reexamined. Of special importance are supernovae which are noted for the overabundance of refractory elements in their ejecta. The contribution of protostellar nebulae is also very uncertain. Finally, methods of producing dust in the interstellar medium (Elmegreen, 1981) or in dense cloud cores, need further investigation. On the other hand, the efficiency for grain destruction may be lower than currently estimated.

The dynamics and the destruction of the dust in various types of astrophysical shocks need to be reexamined in more detail.

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