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ASTRONOMICAL OBSERVATIONS OF SOLID PHASE CARBON

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I. INTRODUCTION

At least half of the material heavier than helium in the interstellar medium is contained within small (10^{-7} - 10^{-4} cm) solid grains (see Spitzer 1978). The nature, composition, origin and evolution of this interstellar dust is still not fully known. Nevertheless, because it is so abundant in the Milky Way Galaxy, carbon is likely to be a major constituent of the interstellar solids. It seems that the solids do not form in the interstellar medium *in situ* because the densities are so low. Instead, the bulk of grain cores form in high density environments such as the envelopes of red giant stars; these nuclei are then expelled into the interstellar medium where the grains may undergo substantial processing (Seab 1987).

In the galaxy as a whole, about 90% by number of the material is hydrogen, nearly 10% is helium, and the rest is "minor constituents". In the standard or "cosmic abundances", oxygen is about twice as abundant as carbon. However, there are a few rare stars where carbon is more abundant the oxygen, the carbon stars. In the *Yale Bright Star Catalogue*, the standard reference on the ~10^4 optically brightest stars, about 20 carbon stars are listed. While carbon stars are quite rare, they are losing large amounts (>10^{-7} $M_\odot$ yr^{-1}) of mass (Claussen *et al.* 1987). Therefore, a substantial fraction, perhaps half, of all the matter injected into the interstellar medium is produced in the carbon-rich environments of carbon stars (Zuckerman *et al.* 1977, Knapp and Morris 1985).

In the outer envelopes of red giants, when the gas cools sufficiently, molecules and solids form. Thermodynamically, the most stable molecule is CO, and it is usually assumed that all the available carbon and oxygen are consumed in the formation of this molecule (Salpeter 1977). If the carbon abundance is greater than the oxygen abundance, then the carbon left over after the formation of CO is available for solid grains. Because carbon is by far the most abundant species available for making solids in these environments, we anticipate that the grains are composed of nearly pure carbon in some form. Below, we discuss the observations which can be used to infer the nature of this solid phase carbon.

It is usually assumed that most of the carbon in any particular environment is ^{12}C. In fact, in most carbon stars, $^{12}C/^{13}C$ = 35 (Lambert *et al.* 1986). However, about 15% of all carbon stars, the J-types, have $^{12}C/^{13}C$ between 2 and 4 (Lambert *et al.* 1986, Jura, Kahane and Omont 1987). In these ^{13}C-rich stars, the solid carbon might exhibit subtlely different properties than the carbon-rich material around the more common carbon stars. However, this difference between the ^{13}C-rich carbon stars and the more ordinary types has not yet been fully explored.

Once the grains are expelled from the carbon star into the interstellar medium, they may not remain intact as carbon-rich material because of the substantial processing that they undergo. However, there is good evidence for the widespread presence of interstellar PAH's, polycyclic aromatic hydrocarbons (see Leger, d'Hendecourt and Boccara 1986). These PAH's are carbon ring molecules containing at least 20 atoms. The relationships between the interstellar PAH's and carbon grains is still not clear.

Aside from carbon-rich red giants, there are other possible sites for the formation of carbon-rich grains. Some Wolf-Rayet (W-R) stars are also carbon-rich, and they might be appreciable sources of interstellar carbon (see Maeder 1983). Most W-R stars are thought to be quite massive (>20 $M_{\odot}$, Abbott and Conti 1987) as opposed to carbon-rich red giants which typically have masses of ~1.5 $M_{\odot}$ (Claussen et al. 1987). However, only a few of the W-R stars show evidence for circumstellar grains in the sense that for most W-R stars, most of the infrared emission is produced by ionized gas in the hot wind (Abbott, Telesco and Wolff 1984). It is a subset of the W-R stars, the cool carbon-rich ones of type WC8, WC9 and WC10 which seem often to contain dust (Williams, van der Hucht and The 1987) since they display strong infrared excesses. For example, in the complete sample of 43 W-R stars north of -40° declination and within 3 kpc of the Sun studied by Abbott et al. (1986), 2 are strong infrared sources in the sense that they have 12 μm fluxes greater than 400 Jy in the IRAS catalog even though they are both more than 1 kpc from the Sun. In contrast to these two unusual stars, the other 41 stars all have 12 μm fluxes in the IRAS catalog of less than 20 Jy and most are not detected at all.

At least some W-R stars actually are transition objects between red giants and planetary nebulae since the central stars of planetary nebulae sometimes have W-R spectra (Kaler 1985). That is, for some stars, there is some ambiguity about whether they are pre-planetary nebulae with a mass of ~1-2 $M_{\odot}$ or are truly massive (see van der Hucht et al. 1981, 1985). It should be noted that Massey, Conti and Armandroff (1987) are unable to find WC8, WC9 and WC10 stars in nearby galaxies even though it is straightforward to find warmer W-R stars. One possible explanation for this result is that at least some of the very cool W-R stars are really just evolved from being red giants with luminosities of ~10^4 $L_{\odot}$ instead of having luminosities >10^5 $L_{\odot}$ that is characteristic of most W-R stars which are thought to be quite massive. In any case, except for the stars which are strong infrared sources, the typical dust loss rates are 10^{-8} $M_{\odot}$ yr^{-1} (Williams, van der Hucht and The 1987), and this suggests that most carbon grains in the galaxy do not result from W-R stars. Therefore, because the evolutionary nature of the IR bright W-R stars is not certain, we do not discuss them in detail in this review. Also, carbon grains might be formed around some novae and even possibly around some supernovae; these processes are not described here because very little is known.

In Section II, we discuss the observations of the dust around carbon-rich red giants, while in Section III we place these results into their broader astrophysical context.

II. Circumstellar Dust Around Carbon-Rich Red Giants

Carbon-rich red giants are thought to be on the Asymptotic Giant Branch with luminosities that are typically ~10^4 $L_\odot$ (Iben and Renzini 1983). The evidence for mass loss from carbon-rich red giants is very strong. These stars exhibit "excess" infrared emission in the sense that the observed flux at infrared wavelengths is substantially greater than what one would expect on the basis of an extrapolation of their photospheric emission (Jura 1986a). Also, these stars are rich sources of molecular line emission (Olofsson 1985) which indicate typical outflow velocities of 15 km s^{-1}. As reviewed previously by Jura (1986b), there are a number of constraints on the nature of the circumstellar grains which are reviewed below.

A.) Solid State Spectroscopy

For a number of years, low resolution spectra ($\Delta\lambda/\lambda = 10^{-2}$) of mass-losing stars have been available (see Merrill 1979; Kleinmann, Gillett and Joyce 1981). Carbon-rich stars often display an SiC feature at 11.3 μm, although there are some carbon stars where this infrared feature is very weak if it is present at all (Baron et al. 1987, Papoular 1988). For most carbon stars, in order to explain the strength of the SiC feature, it is necessary to argue that most of the silicon is contained in the solid phase within SiC (Pegourie 1987). In addition to the well-known SiC feature, there is evidence in the extensive IRAS data base for other features at 8.6, 11.7 and 12.8 μm (Papoular 1988). The origin of these features is not known.

Recently, it has been discovered that some carbon-rich stars display silicate emission at 9.7 μm that is characteristic of oxygen rich material in their circumstellar dust (Willems and de Jong 1986, Little-Marenin 1986), and some of these stars also have H_2O maser emission that is another characteristic of oxygen-rich gas (Benson and Little-Marenin 1987, Nakada et al. 1987). These oxygen-rich features are thought to be present either because in the last few decades these stars have just become carbon-rich from having been oxygen-rich, or, because they are interacting binary stars, one of which is the optically prominent carbon star and another is an oxygen-rich star. Whatever the correct explanation, the material in their outflows is not representative of most circumstellar gas from carbon stars.

Forrest, Houck and McCarthy (1981) have discovered a very broad feature near 30 μm in the spectra of several carbon stars. It is now thought that this feature results from MgS (Goebel and Moseley 1985).

Finally, Draine (1984) has predicted that if graphite grains are present within the outflows from red giants, there should be a sharp, narrow feature at 11.52 μm. No such feature is found suggesting that most of the dust grains in the outflows from carbon stars are not composed of graphite but rather carbon in some other form.

B.) Broad-Band Colors

Another way to constrain the nature of the circumstellar grains is to study the emissivity and/or extinction as a function of wavelength. The infrared emission that results from reprocessing of the stellar light by the circumstllar dust can be modelled to infer the infrared emissivity of the circumstellar grains (see, for example, Rowan-Robinson and Harris 1983, Sopka et al. 1985, Jura 1986a). One difficulty with this procedure is that the density distribution of the grains around the stars can also strongly affect the infrared colors because these colors depend upon the relative amounts of cold and warm grains (see, for example Harvey, Thronson and Gatley 1979). If we assume a constant mass loss rate, dM/dt, and a constant outflow velocity, v, then from the equation of continuity, we expect for the radial (r) distribution of density, ρ, that:

$$\rho = (dM/dt)/(4\pi r^2 v)$$

Either by considering a few very well studied stars or by studying a large sample of stars where, on the average, we expect the density to vary as r^{-2}, we can derive the infrared emissivity as a function of wavelength. Note that if the grain density varied, say, as r^{-1}, the infrared colors would be very different from what is observed for envelopes where the density varies as r^{-2}.

Both analysis of the best-studied circumstellar shell around the star IRC+10216 (Campbell et al. 1976, Le Bertre 1987, Martin and Rogers 1987), and ensembles of carbon stars (Jura 1986a) indicates that a power law emissivity which varies as about $\lambda^{-1.1}$ is a reasonable first approximation of the emissivity longward of 1μm. However, there are differences in the broad-band colors between oxygen-rich and carbon-rich stars (Hacking et al. 1985, Zuckerman and Dyck 1986), and a single power law is not a perfect representation of the emissivity of the grains.

Shortward of 1 μm, the circumstellar grains are not significant emitters. Nevertheless, it is still possible to estimate the wavelength variation of the opacity both from direct observations of the light from the central star and indirect observations of molecules that are subject to photodissociation by the ambient interstellar ultraviolet radiation field. Observations of the Balmer decrement in the spectra of a number of dust-enshrouded carbon stars (Cohen 1979) show a continued rise in the grain opacity toward shorter wavelengths. Also, the large observed spatial extent of HCN around the well-studied carbon star IRC+10216 (Bieging, Chapman and Welch 1984) is most easily understood if the grain opacity continues to rise about as λ^{-1} into the ultraviolet (Jura 1983, Glassgold, Lucas and Omont 1986).

While it is straightforward to estimate the relative infrared emissivity as a function of wavelength, we do not know the absolute number of carbon grains. That is, with the information available, we do not know whether the infrared emssion is produced by a few grains that are efficient emitters or many grains that are inefficient emitters. Experiments show that there is a range of at least a factor of 5 in the infrared emissivity of different sorts of solid carbon (Borghesi, Bussoletti and Colangeli 1985). It seems reasonable to adopt for amorphous carbon, the most likely candidate for the grain material, an opacity at 60 μm of 150 cm^2 gm^{-1} (Borghesi et al. 1985). If χ_{60} denotes the grain opacity (cm^2 gm^{-1}) at 60 μm, then we have for the dust to gas ratio around most carbon stars within a factor of 3 that (Jura 1986a):

$$M_{dust}/M_{gas} = 4.5\ 10^{-3}\ (150/\chi_{60})$$

All the data together indicate that the solid dust around mass-losing red giants is probably small particles of amorphous carbon (see, the detailed discussion by Martin and Rogers 1987).

C.) Grain Sizes

There are some significant observational constraints on the size distribution of circumstellar grains around mass-losing red giants. Because we have less information than is available for intestellar extinction, we cannot argue as in the case of interstellar grains that the size distribution n(a) varies as $a^{-3.5}$ (Mathis, Rumpl and Nordsieck 1977). Nevertheless, there are useful probes of the grains sizes: (i) As noted above, the extinction continues to rise approximately as λ^{-1} even into the ultraviolet. This implies (see, for example, Spitzer 1978) that at least some of the grains are relatively small compared to 1000 Å. That is, grains with sizes large compared to the wavelength of the incident light tend to have a cross section equal to their geometric size and thus have an opacity independent of wavelength. (ii) Circumstellar grains scatter the light from the central star. This is sometimes seen directly as reflection nebulae (see, for example, Yusef-Zadeh, Morris and White 1984). Also, the integrated optical light from carbon stars typically exhibits some net polarization (Dyck, Forbes and Shawl 1971). These data are most easily understood as resulting from scattering by an anistropic distribution of dust grains around the star (Daniel 1982). Because there is appreciable scattering of optical light, many of the grains cannot be much smaller than 1000 Å (Spitzer 1978). That is, if the grains were all much smaller than the wavelength of the observed scattered light, the scattering cross section would be very small. (iii) A final constrant on the size of the grains is the heating of the circumstellar gas. Once the grains form, they stream supersonically through the gas, and this is the main source of gas heating. The amount of heating of the gas is sensitive to the grain size; the CO data for IRC+10216 are most easily understood if the grain size is ~400 Å (Kwan and Hill 1977, Kwan and Linke 1982). The thermal properties of circumstellar envelopes around other stars are also consistent with this value (Jura, Kahane and Omont 1988).

We conclude that there is good evidence that a number of circumstellar grains may have sizes of ~1000 Å. Like interstellar grains, there may be a wide range of sizes, but we know that many of these particles are submicron sized.

III. ASTROPHYSICAL IMPLICATIONS

As reviewed by Jura (1987), stars of all different types are returning about 10^{-3} $M_\odot$ yr^{-1} kpc^{-2} into the local disk of the Milky Way Galaxy. Between 10% and 50% of this material results from carbon-rich red giants. Once the grains from carbon stars enter the interstellar medium, they undergo substantial processing. Therefore, even though we know that there are significant sources of carbon grains, we do not know how well this material keeps its identity as carbon-rich in the interstellar medium.

The strongest known feature in the intestellar extinction occurs near 2200 Å (Savage and Mathis 1979). This feature is often attributed to carbon grains (Mathis, Rumpl and Nordsieck 1977). However, there is not universal agreement with this identification (Duley 1987), and there is no straightforward demonstration of the presence of carbon-rich grains within the interstellar medium itself.

There is an indirect argument that some interstellar carbon is contained within grains of some sort. First, as mentioned above, there is so much material within grains that it is almost certain that they must contain some carbon. Second, we know that the gas phase abundance of carbon is probably depleted by about a factor of 2 or

3 below its cosmic abundance (Hobbs, York and Oegerle 1982, Jenkins, Jura and Loewenstein 1983); it seems likely that there is as much interstellar carbon in the solid phase as there is in the gas phase.

Finally, it should be noted that there is evidence for the widespread presence throughout the interstellar medium of PAH's (Leger, d'Hendecourt and Boccara 1987). These species may be either large molecules or very small grains. However, their origin and evolution within the interstellar medium are still very not well known (Omont 1986). It will be a matter of considerable concern for the future to develop a much deeper understanding of these carbon particles in the interstellar medium and their relationships with the larger dust grains.

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