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OBSERVATIONAL CONSTRAINTS ON CIRCUMSTELLAR DUST

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I. INTRODUCTION

There is an enormous range in the properties of stars are are losing mass. In this review I concentrate on those red giants that are responsible for injecting roughly half or more of the material into the interstellar medium.

During the past 15 years, there has been a dramatic improvement in our understanding of mass loss from red giants. The stars that are losing the most mass are enshrouded by cold envelopes of dust and gas so they are primarily infrared and radio sources; consequently, with the development of appropriate instrumentation, it has been possible to reach a much deeper understanding of the mass loss from these stars. Optically, stars such as IRC +10216, the carbon rich mass losing prototype, are extremely faint, yet at 10 μm, many of the brightest objects in the sky are highly evolved red giants (Kleinmann, Gillett and Joyce 1980).

In this review, I concentrate on describing the physical properties of the outflows. Earlier work has been reviewed by Zuckerman (1980), I focus on the results obtained during the past 5 years. Also I do not, for example, discuss either the importance of the grains in driving the outflows by radiation pressure or models for how the grains might form. In Section II, I describe the physical properties of the gaseous outflows while in Section III, broad-band observational constraints on the dust are described. In Section IV, spectroscopic studies of the grains are reviewed.

II. PHYSICAL PROPERTIES OF THE GAS OUTFLOWS

In almost all the stars of interest, most of the outflowing gas is hydrogen, and the first task is to describe the physical state of this gas. Searches for atomic hydrogen at 21 cm from the outflows from red giants have generally been unsuccessful (Zuckerman, Terzian and Silverglate 1980; Knapp and Bowers 1983). In two special circumstances, α Sco and NML Cyg, some of the circumstellar hydrogen is ionized, and it has been possible to detect the total mass outflow from measurements of the radio free-free emission (Hjellming and Newell 1983; Morris and Jura 1983). However, in most stars, it seems that the bulk of the outflowing gas is H_2. While in a few circumstances the H_2 is excited by shocks (Beckwith, Persson and Gatley 1978); current technology does not enable us to study the bulk of the molecular hydrogen. Therefore, most of the spectral diagnostics of the outflowing material have been performed by studying the minor constituents such as CO, OH and H_2O.

Because it is so stable, standard condensation theories predict that the first molecule to form as the gas cools is CO (Salpeter 1977), and the CO consumes all the available oxygen or carbon. That is, a star is carbon rich and has free carbon only if $[C]/[O] > 1$; otherwise the star is oxygen-rich. The expectation that CO is abundant in the outflows from late-type giants is well supported by observations, and a convenient way to study the circumstellar CO has been its radio emission. Recent surveys have increased to roughly about 100 the number of stars from which CO has been detected in the radio (Knapp and Morris 1985; Zuckerman and Dyck 1985).

From observations of the radio CO profile, it is directly possible to measure the outflow velocity from the full width at zero intensity of the line (for example, Morris 1975). The characteristic outflow speed is 15 km s^{-1}; outflow velocities range from 4 km s^{-1} to greater than 40 km s^{-1}. The outflow velocity is correlated with the period of pulsation of the red giant (Morris et al. 1979) suggesting that pulsations may be related to the rate of mass loss (see also DeGioia-Eastwood et al. 1981). Also, at least in oxygen-rich stars, with considerable scatter, it appears that v varies as $L^{1/4}$ (Jura 1984b).

With relatively few assumptions, it it also possible to derive the mass loss rate, M, from the radio CO observations. The CO radio lines are excited by collisions with ambient H_2 and by flourescence that results from absorption in infrared vibrational transitions. From the shapes of the radio line profiles, the relative intensities of the J = 2-1 and J = 1-0 rotational transitions and, in some cases, maps of the CO emission, it is possible to derive mass loss rates (Kwan and Hill 1977; Morris 1980; Jura 1983b, Knapp and Morris 1985). The major uncertainties in the analysis are the abundance of CO relative to H_2 and the distance to the star.

In the usual evolutionary scenario, these mass-losing red giants evolve into planetary nebulae (Zuckerman et al. 1977; 1978). Since observations of planetaries do not show large variations in the total amount of CNO ejected into the interstellar medium (Zuckerman and Aller 1985), the uncertainties introduced by assuming a CO abundance in the outflow are probably not dramatic. Also, while the total mass loss rate of an individual star is sensitive to the assumed distance, some relative quantities such as the dust to gas ratio in the outflow are not.

Mass loss rates from red giants cover a very wide range. The highest known values are about 10^{-4} $M_{\odot}$ yr^{-1} while there are positive detections of loss rates as low as 10^{-8} M_0 yr^{-1}. This upper limit is probably significant since the large majority of these red giants are asymptotic giant branch stars approaches the maximum theoretical luminosity of 6 10^4 L_0 (Iben and Renzini 1983). If radiation pressure on the grains drives the matter to infinity, then $Mv \leq L/c$ and with $v = 15$ km s^{-1}, this implies that $M \leq 10^{-4}$ M_0 yr^{-1}. Although a few years ago it was suggested that for carbon-rich stars, Mv could be considerably larger than L/c (Knapp et al. 1982), this no longer seems to be the case (Jura 1983, Knapp 1985).

A number of important results appear in the recent survey of mass loss by Knapp and Morris (1985). Some important though still tentative findings are:

1. The mass injected into the interstellar medium by carbon-rich and oxygen-rich stars appears to be roughly comparable. (This result is in striking contrast to the optical observations that there are many more oxygen-rich stars than carbon-rich stars, a discrepancy first noted by Zuckerman et al. 1977).
2. A wide range of stars contributes to the mass ejected into the interstellar medium. As a first approximation, the amount of mass contributed by stars with mass loss rates of 10^{-4} yr^{-1} is comparable to the amount contributed by the many more stars losing 10^{-7} M_0 yr^{-1}.
3. At least 0.3 M_0 yr^{-1} are returned to the interstellar medium to the entire Galaxy by mass loss from red giants. This is at least comparable to and probably larger than all the other sources of new interstellar matter. However, because their sample of stars was not chosen on some systematic basis, definitive conclusions will not be reached until the recent comprehensive survey by Zuckerman and Dyck (1985) is completed.

Other molecules besides CO have also been used to study circumstellar shells. In oxygen-rich stars, OH, H_2O, SiO (see Zuckerman 1980) and most recently H_2S (Ukita and Morris 1983) have been found while in carbon-rich stars, a number of molecules have been found (Lafont, Lucas and Omont 1982) including, most recently, SiC_2 (Thaddeus, Cummins and Linke 1984). As described below, there is also recent evidence that large polycyclic aromatic hydrocarbons may be present in large numbers.

Isotope ratios in the mass outflows from stars can be measured in the optical, infrared and radio spectra; however, at all wavelengths there is often some ambiguity in interpreting the data. By far the most commonly studied isotope ratio is $^{12}C/^{13}C$. For α Ori, an oxygen-rich supergiant, it appears well established from infrared observations that $^{12}C/^{13}C = 6$ (Bernat et al. 1979). In the well studied carbon star, IRC +10216, the recent infrared data (Keady, Hall and Ridgway 1985) give $^{12}C/^{13}C = 35$ in reasonably good agreement with most of the older studies (Zuckerman 1980). This difference in the $^{12}C/^{13}C$ isotope ratio between these two particular stars may be characteristic of oxygen-rich and carbon-rich stars that are losing large amounts of mass. That is, Knapp and Chang (1985) find from radio measurements that $^{12}CO/^{13}CO$ is generally larger in carbon-rich stars compared to oxygen-rich stars. Also, optical studies of oxygen-rich red giants indicate $^{12}C/^{13}C$ ratios around 10 (Hinkle, Lambert and Snell 1976) which is much lower than the interstellar value of 43 ± 5 (Hawkins, Jura and Meyer 1984) and therefore cannot be characteristic of the bulk of the matter which is injected into the interstellar medium. Since carbon-rich stars contribute much of the new mass of the interstellar medium, this indirectly suggests that carbon-rich stars have $^{12}C/^{13}C$ ratios high compared to 10. Unfortunately, classical optical spectroscopy of carbon-rich stars has not lead to precise measurements of isotope ratios. As discussed by Dominy et al. (1978) and Johnson, O'Brien and Climenhaga (1982), the inferred range for $^{12}C/^{13}C$ in the well studied carbon star V 460 Cyg is between 7.9 and 100, although the best current value is around 30.

III. BROAD BAND OBSERVATIONS OF THE GRAINS

One of the most striking results of observations of mass outflows from late-type giants is that there is a strong correlation between the gas loss rate and the amount of grains measured by their infrared emission (Zuckerman and Dyck 1985). From the observed infrared emission, it is possible to infer the dust loss rate, and this value can be compared to the gas loss rate derived from radio CO measurements described above. It has been found that while there may be fluctuations, gas to dust ratios by mass of about 100 seem to obtain (Knapp 1985, Sopka et al. 1985). In other words, for solar abundances, most of the refractory material that conceivably could be condensed onto solids actually does so. Indirect observational evidence of the gas also supports this conclusion. For example, only about 1% of the silicon is contained within gas phase SiO even though this is thought to be the major form of this element in the gas. This result is consistent with the view that most of the silicon is contained within grains (Morris et al. 1979; Jura and Morris 1985).

It seems well established that not only do the grains contain a large fraction of the material other than volatiles such as hydrogen and helium, it seems that the circumstellar grains also have sizes not too dissimilar from interstellar grains. That is, with some considerable uncertainty, there is evidence that many of the grains have sizes within an order of magnitude of 0.1 μm. The evidence is the following:

1. Optical observations of quantities such as the intensity of Hα/Hβ emission lines in carbon stars indicate considerable circumstellar reddening (Cohen 1979). Also, molecules such as H_2O and HCN are photodissociated by ambient interstellar ultraviolet photons as they flow out of the star (Goldreich and Scoville 1976, Huggins and Glassgold 1982, Jura 1983a). Interpretation of the spatial distribution of these molecules indicates that the extinction probably continues to rise in the ultraviolet. Therefore, most of the particles in circumstellar outflows are probably not larger than 0.1 μm; otherwise the extinction would not be a strong function of wavelength.

2. Polarization of the optical (Shawl 1974) and near infrared radiation (Dyck et al. 1971) can be interpreted in terms of grains of roughly 0.1 μm size (Daniel 1982). That is, not all the grains are very small; otherwise there would be no effective scattering.

3. In the outer circumstellar envelope ($r > 10^{15}$ cm), the gas is heated by the grains streaming supersonically through the gas (Goldreich and Scoville 1976). This heating rate is sensitive to the grain size, and at least in the case of IRC +10216, the best studied circumstellar envelope around a carbon star, it appears that the mean size of a grain is 0.04 μm (Kwan and Hill 1977).

4. Papoular and Pegourie (1983) have suggested that the shape of the 10 μm feature in oxygen-rich stars requires some grains with sizes comparable to 1 μm. While it is important to understand the nature of the profile variations among different sources, this could be a result of temperature or compositional differences rather than grains having different sizes.

The overall infrared energy distribution of the light from circumstellar dust shells seems to be well understood (Rowan Robinson and Harris 1983a,b; Sopka et al. 1985). Models of the observations are most consistent with a grain emissivity that is modelled by a power law which varies more like $\lambda^{-1.2}$ rather than λ^{-2} (Campbell et al. 1976, Werner et al. 1980, Sopka et al. 1985). In carbon stars, this suggests that the grains are more likely to be composed of amorphous carbon rather than graphite.

The presence of near infrared emission indicates that some of the grains are relatively warm with temperatures near 1000 K. This is an important constraint on any formation mechanism of the grains. Also, interferometry indicates that the grains are formed within 10^{15} cm of the stars (Sutton et al. 1977, 1978, 1979, Dyck et al. 1985). This result also suggests that the temperature of formation is near 1000 K.

A very indirect argument on the location of the grain formation comes from the observed outflow velocities. If the gas to dust ratio is 100, we expect that once the grains form, radiation pressure overpowers the gravitational force exerted by the star and drives the material to infinity. If the grains form close to the star, then the outflow velocity is predicted to be larger than the characteristic speed of 15 km s^{-1}. On the other hand, the result that v varies as $L^{1/4}$ is consistent with condensation of a large amount of material at 1000 K (Gehrz and Woolf 1971, Jura 1984a) or roughly 10^{15} cm from the star of luminoisity 10^4 L_0.

A final point is that the line profiles in circumstellar outflows may provide valuable information on the condensation sequence. In the spectrum of

IRC+10216, Keady, Hall and Ridgway (1985) have measured broad troughs in the P Cygni lines. A possible model to explain the observations is that as the grains cool in the outflow, they can accumulate molecules that were too volatile to condense onto the solid at the higher temperature characteristic of the grains closer to the stars. Rapid accumulation of mantles might occur at preferred temperatures and this would result in impulsive acceleration of the material as the grain opacity becomes larger (Jura 1984b). Therefore, it may be possible with sufficiently good data to indirectly infer the condensation sequence in the outflow from a star.

IV. SPECTROSCOPY OF CIRCUMSTELLAR DUST

Although the broad band measurements can provide useful constraints on the nature of the dust, they do not provide nearly as much information on the detailed structure of the grains. Merrill (1979) and Kleinmann, Gillett and Joyce (1981) have reviewed the observations of the spectra of red giants. A major result is that the oxygen rich stars display the silicate features at 9.7 μm and 18 μm while the carbon-rich stars show SiC at 11 μm. Since 1980, there have been a number of recent advances of our understanding of the grains:

1. Forrest, Houck and McCarthy (1981) have discovered a feature near 30 μm in the spectrum of carbon-rich stars. The nature of the carrier remains unidentified.
2. Draine (1984) has predicted the presence of a feature at 11.52 μm in the spectra of carbon-rich stars if the grains are composed of graphite. The absence of this feature in the spectrum of IRC +10216 is consistent with the view that the material is more likely to be amorphous carbon than graphite.

3. A few oxygen rich stars show absorption at 3.1 μm characteristic of ice (see, for example, Soifer et al. 1981). Jura and Morris (1985) have argued that gas-phase H_2O condenses onto grains once the dust temperature falls below 110 K at a sufficiently large distance from the star. Quantitatively, this model explains the presence of both gas-phase and solid-phase H_2O around OH 231.8+4.2, the star with the strongest known ice band.

4. A remarkable advance in our understanding of the spectra of the solid state material comes from the study of "unidentified" infrared emission bands between 3.3 μm and 11.3 μm. That is, in a variety of objects such as the carbon-rich planetary nebula NGC 7027, much of the radiation is carried in discrete bands rather than in a continuum (Russell, Soifer and Willner 1977). Just before NGC 7027 became a planetary nebula, it was a red giant (Zuckerman 1977, Jura 1984b) and we still can detect the outer molecular shell surrounding the inner ionized gas. The diffuse IR lines are produced at least in part in the outer molecular gas (Aitken and Roche 1983, Isaacson 1983).

The identification of the infrared features with various vibrational modes of carbon carbon bonds and carbon hydrogen bonds was suggested by Duley and Williams (1981). In an important advance, Leger and Puget (1984) described quantitatively how the observed emission features naturally result from the absorption of ultraviolet radiation by very small (~50 atom) grains; the equivalent of very large molecules. By comparing the observed spectra with laboratory studies, Leger and Puget suggested that polycyclic aromatic hydrocarbons (PAH's) are the best candidates to explain the infrared features. While there is some question as to the exact nature of these molecular carriers (Allamandola, Tielens and Barker 1985), there seems to be a good chance the basic identification of PAH's in circumstellar outflows is correct.

The proposal that the IR bands are carried by PAH's does not, by itself, describe the molecular composition. The observed bands are characteristic of specific bonds rather than specific molecules. For precise identifications, it will probably be necessary to acquire spectra of the electronic transitions.

Quite remarkably, there is some possibility that the PAH's can also explain a 50 year old problem --the origin of the diffuse interstellar bands observed optically. Leger and d'Hendecourt (1985) and van der Zwet and Allamandola (1985) have proposed that these features may be carried by PAH's that are generally present in the interstellar medium. While laboratory data do not (at least yet) support this suggestion, it may be that we do not know enough about the optical spectra of the appropriate molecules because they are ionized or are otherwise modified from normal laboratory specimens, and therefore they have not been intensively studied.

In related observations, Pritchett and Grillmair (1984) have discovered the presence of the diffuse bands 5780 Å and 5797 Å in the spectrum of NGC 7027, a carbon-rich planetary nebula that has just evolved from the red giant stage. Because much if not all of the extinction toward this object is circumstellar rather than interstellar (Jura 1984b), it is distinctly possible that the diffuse bands are carried by large carbon-rich molecules, such as the PAH's. A search for the features in oxygen rich circumstellar shells was not successful (Snow and Wallerstein 1972, Snow 1973), but further work is appropriate.

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