PART IX

CIRCUMSTELLAR DUST

CIRCUMSTELLAR INFRARED EMISSION

I: *The Circumstellar Origin of Interstellar Dust*

NEVILLE J. WOOLF

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minn., U.S.A.

Abstract. Infrared astronomy has in the past decade emerged from being a part-time occupation of a few astronomers. Three major subdivisions of research have become apparent, solar system, galactic and extragalactic studies. In each of these fields infrared studies have made unique contributions. Planets emit the bulk of their radiation in the infrared, and infrared studies are essential to study planetary thermal problems. Many extragalactic objects have been found to emit astonishingly large fluxes in the infrared.

In galactic astronomy the current major contribution of infrared studies has been to act as a bridge between two separate disciplines, stellar astronomy, and studies of the interstellar medium. Infrared studies have proved invaluable for studying star birth and star death. Both of these phases had previously seemed mysterious and invisible. And indeed they were not visible, because they occurred shrouded in dust that blocked transmission of visible rays. However, the dust that is merely opaque in the visible, is self-luminous in the infrared, and so in the midst of this optical darkness there has appeared a great infrared light.

At this time, we have progressed further with the study of star death than of star birth. The ejected matter from dying stars carries the dust shroud with it into space, and so the gas and dust become part of the interstellar medium. This process is clearly significant for understanding the composition and origin of interstellar dust.

Because star death and birth are embedded in dust, there has developed a separate interest in explaining the physical processes at work in these dust clouds. This study explains processes of optical circumstellar absorption lines, intrinsic polarization of cool star light, and stellar molecular masers.

Perhaps what these two paragraphs have just said is that our conceptual scheme of separating stellar astronomy and interstellar astronomy still acts as such a division that the infrared astronomer needs to present different aspects of this one topic, circumstellar infrared emission to different audiences. Such an opportunity has been given to the author in that he has been asked to give within a few weeks two talks. The first of these reviews is being presented at IAU Symposium # 52 on Interstellar Dust and Related Topics. The second is being given at the summer meeting of the Astronomical Society of the Pacific which has a symposium on Circumstellar Dust.

The two reviews have been made complementary. The first of these is primarily an observational study. It shows the infrared observations of stellar and interstellar dust, and in a qualitative way shows that one gives rise to the other. The second review is theoretical and attempts to place the first study in its theoretical context. It deals almost exclusively with the stellar and circumstellar parts of the topic. Together they present one man's view of *Circumstellar Infrared Emission*.

The literature relevant to this topic is voluminous. There have been false leads, dead ends, and irrelevant detail. This review has attempted to follow a thread through this detail, and to expose the skeleton of a scheme for understanding the processes at work. Such a review is intrinsically more dangerous, more likely to become obsolete than a comprehensive one. However, by carrying the seeds of its own destruction it seems to offer a greater opportunity for the growth of astronomy.

1. Theories of the Origin of Interstellar Dust

There are two and a half hypotheses about the origin of interstellar dust. The first is that it condenses in interstellar space, the second that it condenses in stellar envelopes and atmospheres, and the half hypothesis combines these by making condensation

Greenberg and Van de Hulst (eds.), Interstellar Dust and Related Topics, 485–504.

https://doi.org/10.1017/S0074180900054668 Published online by Cambridge University Press

nuclei from circumstellar dust, but having the bulk of the material as more volatile materials that could condense in interstellar space.

This review presents arguments in favor of the second hypothesis. First, it collects the infrared evidence for the composition of interstellar dust from studies of emission and absorption spectra of diffuse matter. Then it discusses the observations of circumstellar matter around evolved objects, where dust is clearly not a remnant of the proto-stellar cloud. Some brief comments, for completeness, show how the circumstellar clouds around young objects compare with these. Finally, there is a discussion of the nature and origin of interstellar dust. Many of the observations discussed here are presented in other contexts in a comprehensive review article by Neugebauer *et al.* (1971).

2. Emission and Absorption Spectra of Diffuse matter

This past year Gillett has constructed a scanning spectrometer with resolution 0.1 μ for the spectral range 3–14 μ. This sensitive device employs a copper doped germanium photoconductive detector, and a cold, circular, variable wavelength pass-band filter wheel. Figures 1–6 show observations made by UCSD and University of Minnesota observers with this spectrometer attached to a 60 in telescope at Mt. Lemmon Infrared Observatory.

Figure 1 from Gillett and Stein shows the emission spectrum of the trapezium region of the Orion Nebula. No bright stars were admitted by the spectrometer entrance aperture. Note that the emssion peaks at 9.7 μ declines rapidly to short wavelengths, and slowly to long wavelengths. Photometric results, e.g. by Ney and Allen (1969) show that there is then a further rise into the 20 μ region. Because the emission decreases rapidly to wavelengths shorter than 9.7 μ, it is apparent that no other

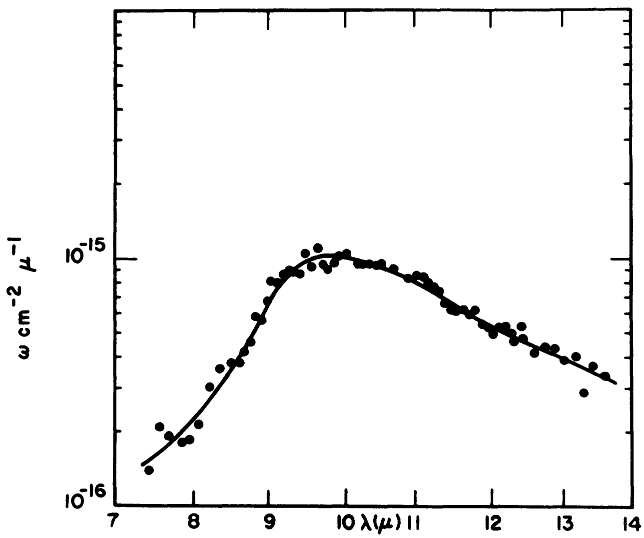

Fig. 1. Spectrum of the trapezium region of the Orion Nebula. The feature is silicate emission.

https://doi.org/10.1017/S0074180900054668 Published online by Cambridge University Press

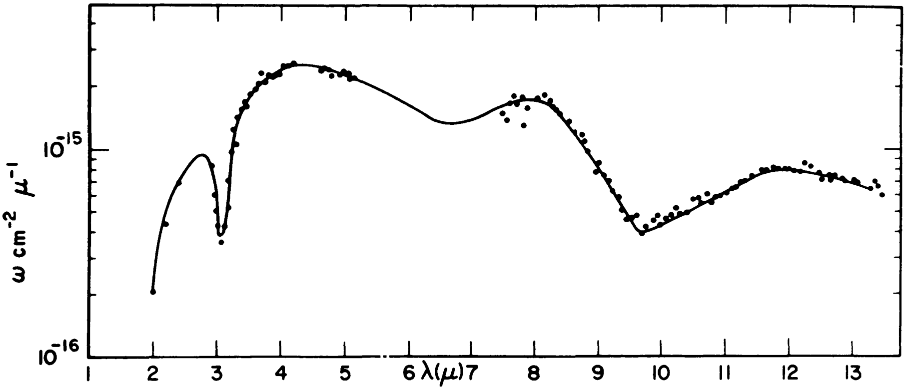

Fig. 2. Spectrum of the Becklin-Neugebauer star with wings embedded in the Kleinmann-Low infrared nebula in Orion. The 3.1 μ band is identified as ice, and the 9.7 μ feature is silicates.

source of emission has become significant in the 7–8 μ spectral band. If there is more than one solid material present here, and one produces the 9.7 μ feature, and the second material produces a warmer, black-body like spectrum, as one might expect for graphite or iron, then there is not very much of this second material present here.

Figure 2 from Gillett, Forrest and Cohen shows the Becklin-Neugebauer 'star with wings' that is in or behind the Kleinmann-Low infrared nebula in Orion. Additional observations with different size diaphragms show that out to 12 μ almost all of the energy comes from the starlike object. Note the two strong absorptions in this spectrum, one peaking at 9.7 μ, and the other at 3.1 μ. The 9.7 μ feature looks like an inversion of Figure 1, though the peak appears a little sharper.

The 3.1 μ feature appears at the same wavelength as a feature seen in CIT+40°448 (NML Cygni) and some stars, but not seen in others, e.g. the B star VI Cygni #12 that suffers about 10 magnitudes of interstellar extinction (Danielson *et al.*, 1965; Knacke *et al.*, 1969; Stein *et al.*, 1969b; Low *et al.*, 1970). It seems probable that this feature is due to interstellar ice. A second band, weaker in equivalent width by a factor 3 should be present at 12.5 μ, or possibly resolved into two features at 11.5 μ and 13.5 μ. However, because of the greater width of this feature, the band should be so shallow that its absence is perhaps still compatible with the ice identification. The amount of ice needed to produce the 3.1 μ band is $\sim 6 \times 10^{-5}$ gm cm^{-2}.

If the 9.7 μ feature is identified as a silicate absorption band, and a band strength of 3000 cm$^2 \cdot$ gm^{-1} at the peak is assumed, then 4×10^{-4} gm cm^{-2} of silicate are in the line of sight. However, Hackwell (1971b) found that a carbonaceous chondrite, composed of $\sim$ 70% silicate, and with absorption spectrum resembling Figure 2 required about 3 times as much matter to produce this absorption, thus the amount of silicate may be as high as 10^{-3} gm cm^{-2}. There is 6–20 times as much silicate as ice present.

Figure 3 from Woolf and Gillett shows the spectrum of the infrared core at the galactic center observed with a 22″ diam diaphragm. Note that peak absorption also occurs here at 9.7 μ, and the optical depth is $\tau \approx 4$. Earlier broadband observations by Low *et al.* (1969), and Hackwell *et al.* (1970), had suggested $\tau \approx 0.5$ both in this

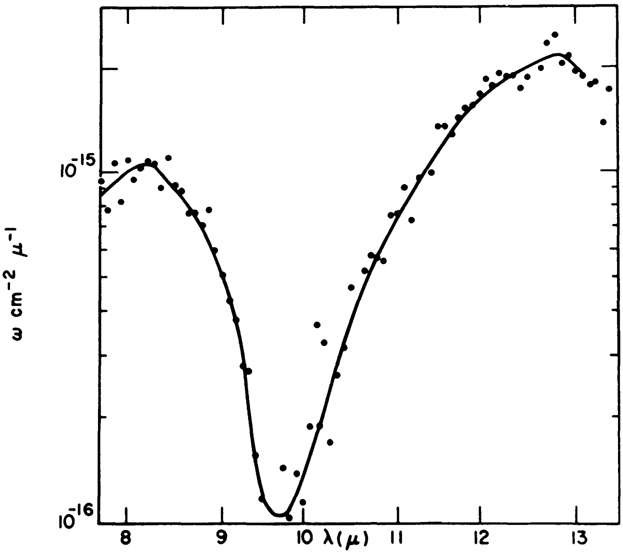

Fig. 3. Spectrum of the IR core of the galactic center.

band, and a 20 μ band. The new observation seems quite certain, being a mean of four separate scans, and preliminary observations at an earlier time had also indicated a large optical depth. Apparently the broadband photometry washed out the feature by a large factor.

A very weak possible absorption appears near 12.5 μ. If this is an ice band, then at most $\tau \approx 0.2$. This value is probably consistent with the ratio of silicate to ice indicated by the Orion point source.

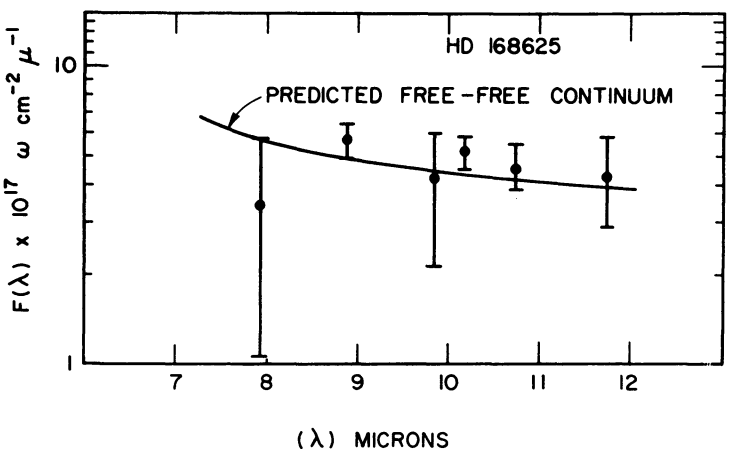

Fig. 4. Points in the spectrum of HD 168625 B8Ia^{+}. This star suffers about 5.7 mag. visual interstellar extinction.

Stein and Gillett (1971) made broadband 10 μ region observations of VI Cygni #12 to search for an interstellar silicate absorption. They concluded that $0.1 > \tau$. If, however, we make some correction as with the galactic center for washing out of the feature, then more probably $0.3 > \tau$. Thus the ratio of visual extinction for this object to silicate absorption at the peak is greater than 30:1. For the Orion point source 1–2 μ spectral distribution implies a visual extinction close to 70 mag., giving its ratio of visual/IR silicate absorption 50:1. However, if we assume that the extinction to galactic center stars of 25 ± 5 mag. (Becklin and Neugebauer, 1968) also applies to the IR core, we have a ratio of about 7:1. Clearly if the line to the galactic center is typical, then the silicate absorption of the Orion object and VI Cygni #12 is weak. Or if these two objects are normal, then the galactic center core has much local extinction, with a total visual extinction of about 200 mag. Such absorption is compatible with radio molecular line studies.

In order to dinstinguish between these possibilities, Gillett and Woolf have observed a few points in the spectrum of a different reddened star HD 168625, B8Ia$^+$. This star has a slightly elevated 10 μ continuum, probably because of free-free emission. It has an otherwise very similar companion, with a visual extinction of $5^m_.7$ (Hackwell *et al.*, 1970). Both are seen through the dense dust cloud at the edge of M17, giving us a good indication that this extinction is not circumstellar. Figure 4 shows six points in the spectrum of this rather faint object. The uncertainties are very high, but for this object $0.3 > \tau_{9.7}$. Thus the ratio of visual to silicate absorption is >20. This shows that the value obtained in Orion is likely to be correct, and that the extinction of the object at the galactic center is vastly greater than that found for the stars in the galactic bulge.

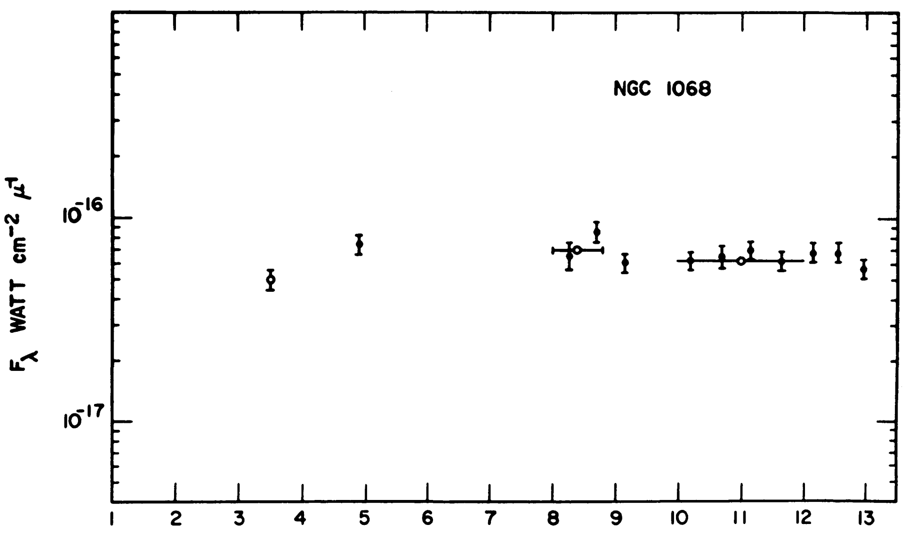

Fig. 5. Points in the spectrum of the Seyfert galaxy NGC 1068.

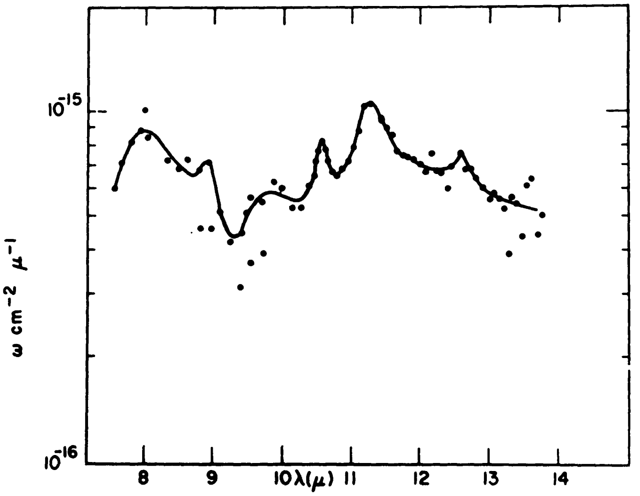

Fig. 6. The spectrum of the planetary nebula NGC 7027.

Figure 5 from Stein, Gillett and Merrill is a similar set of spaced points for the Seyfert galaxy nucleus NGC 1068. This spectrum appears featureless. If the emitting material is a solid, then either it is remarkably optically thick, or it does not have the same spectral characteristics as Figures 1–3. Emission from a conducting or semi-conducting solid such as iron or graphite could cause an appearance like this. Or a non-thermal process could be responsible.

Figure 6 from Gillett, Forrest and Stein shows the spectrum of the planetary nebula NGC 7027. There appear to be sharp emission features, two of which can be identified with lines of A III and S IV. (Delmer *et al.*, 1967). A feature near 12.5 μ seems at too short a wavelength to be Ne II 12.8 μ. A broad feature near 11.3 μ is probably a blend of two or three unidentified lines. A line of Cl I is the only known line in this region. With $3\overset{m}{.}2$ of visual extinction, the spectrum is not appreciably modified by interstellar silicate absorption. If the 11.3 μ feature is *not* resolvable, then Gillett points out a remarkable resemblance between the entire emission spectrum and that expected from hot $MgCO_3$ solid particles. Gillett has also observed the broad 11.3 μ feature in the planetary nebula BD+30°3639. The general shape of the spectrum and depression in the 9.5 μ region repeats earlier observations by Gillett *et al.* (1967). If enough features can be identified to leave a smooth continuum unexplained, then again as in NGC 1068 iron or carbon particles could be responsible. However, because protons would combine with carbon, iron would be more likely here.

3. Solar System Condensates

In the past few years, meteorite research has in general concluded that many meteorites condensed directly from the vapor phase. Some of the more curious boundaries between crystalline iron-nickel and silicate droplets can then be explained. In this model, at some phases iron condenses as a metal from the gas, while at other times it condenses in silicates. At lower temperatures it sometimes forms magnetite Fe_3O_4, and condenses with silicates of unusual structure, and with ring carbon compounds to form carbonaceous chondrites.

The presence of metallic iron is a puzzle. Arrhenius and Alfvén suggest that grain growth is limited by the sticking coefficient of materials, and that neutrals stick better than ions. Iron would then be a condensate of phases where a gas is mildly ionized. However, regardless of the explanation, processes that occurred in the solar nebula should occur elsewhere, and both silicates and iron should be found in astrophysical environments.

The evidence for direct condensation of silicates is important, because the spectra of these materials show two bands near 10 and 20 μ, similar to those found for the Orion trapezium region, and the galactic center. These features have also been found in diffuse matter in the solar system. Comet Bennet was observed photometrically by Maas *et al.* (1970), and showed a 10 μ peak. Hackwell (1971a) studied the 10 μ peak spectroscopically and found it to have the same energy distribution as the supergiant μ Cephei, or essentially that of Figure 1. Comet Bennet also showed a weaker continuum of black body character that was probably iron since in Comet Ikeya Seki, Westphal and Becklin (1966) found a similar continuum existed to color temperatures greater than 1000 K.

The current basis of the silicate identification will be discussed in Paper II. Originally the identification as a solid emitter was made from some elaborate arguments. The circumstantial evidence given here is used here as adequate evidence for the identification of the 9.7 μ feature as silicates.

4. Dust Around Cool Evolved Stars

Cool evolved stars fit into one of three broad categories, M, S and C. The chemical compositions for these types probably have a decreasing oxygen to carbon ratio through the sequence with a near equality at the boundary between S and C. It also seems probable that both oxygen and carbon are depleted in a number of carbon stars with the beneficiary being nitrogen.

Hackwell has obtained photometric observations of M, S and C stars (Hackwell, 1971b). Figures 7 and 8 show that M and S stars show a double humped feature with strong emission near 10 μ and 20 μ, whereas C stars show a single feature near 10 μ. The subtle differences between the different M and S stars may imply slightly different materials being present, or that in some cases the material is optically thick.

Gillett *et al.* (1968) published spectra of one S star and a few M stars all of which had emission excesses closely resembling Figure 1 (see also Woolf and Ney, 1969). An example of a cool star in which the dust seems optically thick, R Aqr, has been published by Stein *et al.* (1969).

The emission around carbon stars has been spectroscopically studied by Hackwell

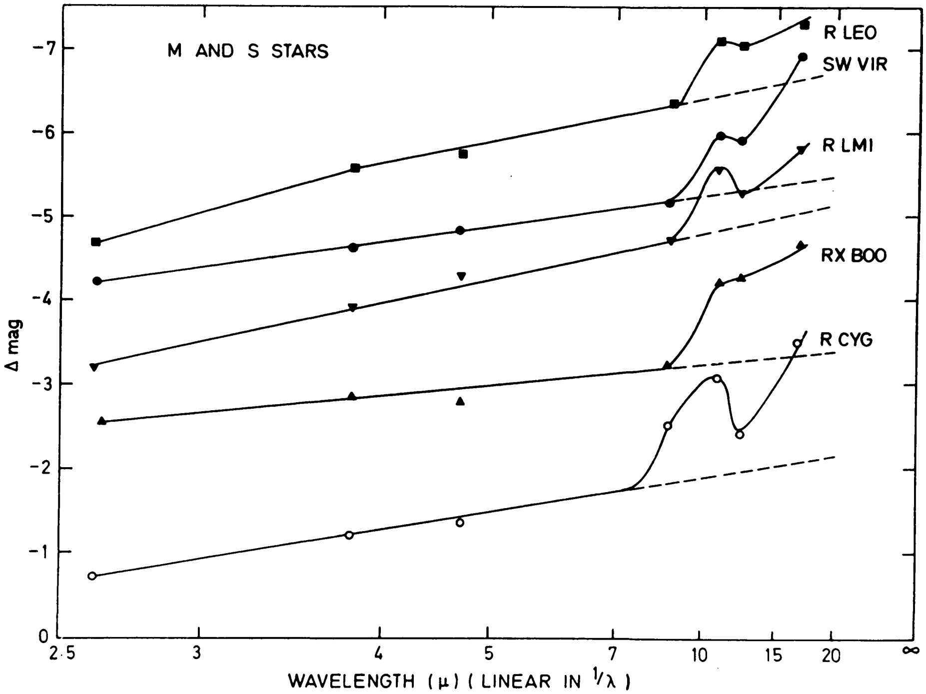

Fig. 7. Photometric measures of M and S stars.

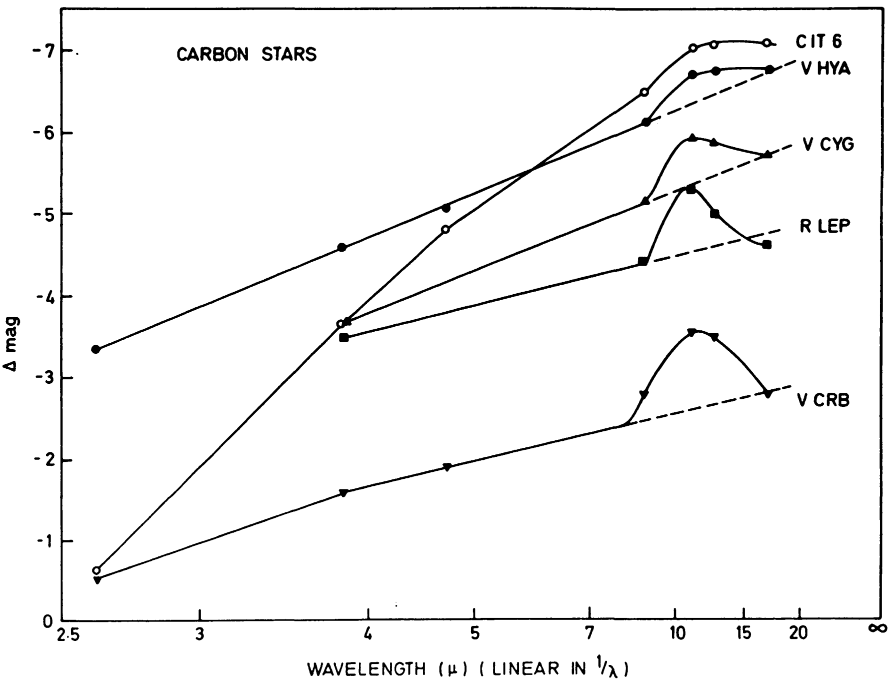

Fig. 8. Photometric measures of carbon stars.

https://doi.org/10.1017/S0074180900054668 Published online by Cambridge University Press

in +30°219 (CIT6) and V Hya. The excess seen in Figure 9 is tentatively ascribed to Si_3N_4. If carbon is not very abundant in the first place, and what there is condenses at high temperatures as graphite, then a mixture is left with a little C and O as CO, and a great deal of nitrogen. On further cooling, the next condensate would be iron, and after this one of the first condensates with obvious spectral features would be Si_3N_4. It is not clear whether carbon stars are producing carbon and/or iron dust. The absence of clearcut spectral features makes identification very difficult. However, the temperature implied by the long wavelength continua of most of the carbon stars in Figure 8 are close to 2000 K, and this is just about the temperature of condensing carbon.

For cool stars of normal composition, the variation of the silicate feature with spectral type has been well studied. It seems to arise in all stars later than a certain spectral type, the type being luminosity class sensitive. This boundary is at G0Ia$^+$, G8Ia, M1Iab, M5Ib and M6III. Figures 10, 11 and 12 from Gehrz (1972) give examples of stars with and without silicate excesses. Some of the observations are from Humphreys *et al.* (1971).

There are a few exceptions of stars earlier and later than these boundaries that do not obey the rule stated above, thus VV Cephei with an M2I a component does not show an excess. On the other hand, the SRa variable RY UMa, M2–3III shows a substantial peak.

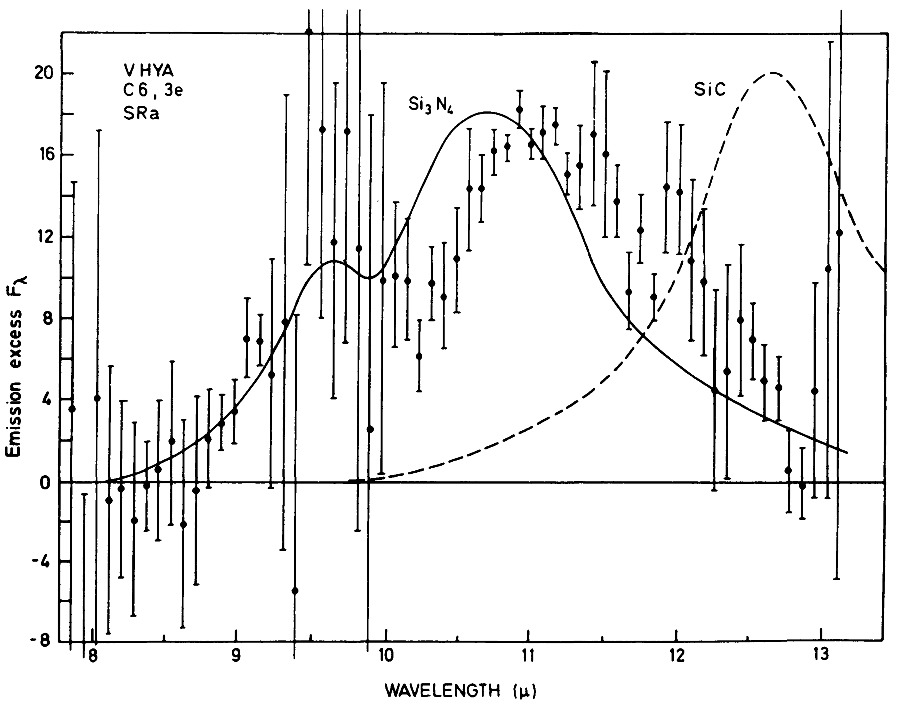

Fig. 9. Average excess above a black body for the carbon star V Hya.

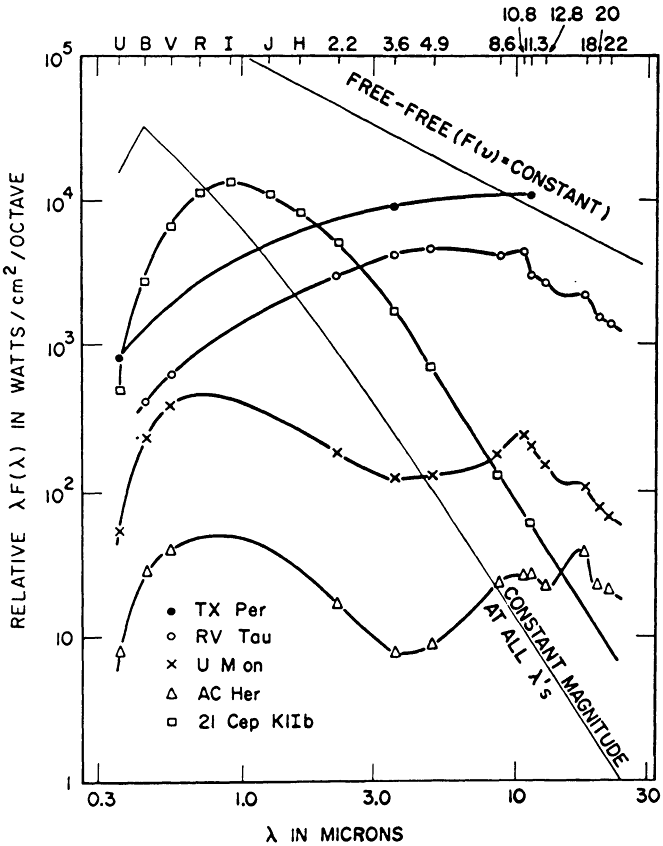

Fig. 10. Photometric measures of giant stars of luminosity Ib.

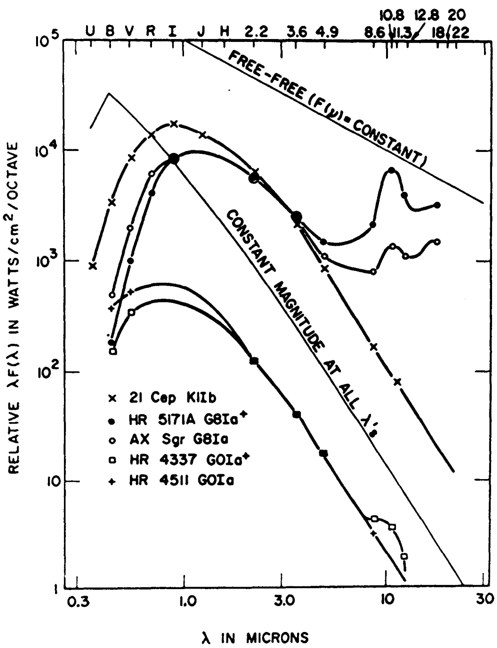

Fig. 11. Photometric measures of G supergiants.

Woolf and Pepin (1972) observed five Mira stars of early spectral type, period about 200 days, and high space motion. All these stars showed excess emission. However, the observations were interpreted as showing dust condensing in a more compact, high gas density shell than for more normal Mira stars. It was inferred that stars in globular clusters perhaps as heavy element rich as Messier 3 would show the phenomenon of circumstellar emission.

It should be noted that thus far the infrared emitting cloud has only been resolved on the sky for the one carbon star CIT +10216 (Toombs *et al.*, 1972). However, circumstellar gas has been resolved a few seconds away from α Herculis by Deutsch (1956), and this star shows a weak silicate double feature (Figure 10).

A number of stars were found in the CIT 2 μ sky survey (Neugebauer and Leighton, 1969) to have apparently very low temperature continua. Some of these appear to be cool M or S Mira variables showing silicate emission peaks. One star +40°448 (NML Cygni) is particularly mysterious. It has a near IR spectrum resembling an M giant rather than a supergiant; however, radio maser observations show outflowing gas to have velocities more characteristic of supergiants. There is a 3.1 μ band in the spectrum possibly indicating interstellar ice absorption. At 9.7 μ there is neither a peak nor a trough. However, interstellar absorption could be exactly compensating for circumstellar emission. If the star is indeed a relatively normal giant, then it is remarkably close, and suffers extra-ordinarily large absorption.

Both NML Cygni and the M5Ia star VY CMa are believed to be evolved. Davies *et al.* (1972) interpret some OH circumstellar features as showing rotating circumstellar clouds for these two stars. Such rotation, if confirmed, would imply such large angular momentum that one would need to assume these were protostars. However, Woolf (1971) explained optical polarization of such stars by asymmetric envelopes. The observations of Davies *et al.* follow the pattern of radial velocities predicted by Woolf, with a core apparently moving towards the observer, and a halo at the star's velocity. Similarly the asymmetric expansion predicted by Woolf would also lead to gas motions that Davies *et al.* would interpret as rotation. For more details see part two, Section 6. The main argument that these are indeed evolved stars is simply a probabilistic one. Time scales of protostar phases are very short compared with thermonuclear burning phases.

5. Dust Around Warm Evolved Stars

G and K type Ia and Ia$^+$ supergiants have silicate emission that appears to be an extension of the phenomenon that occurs with lower luminosity cool stars. Spectra of some of these stars show no optical emission lines, confirming that one is not seeing interstellar emission as in Figure 1.

Some pulsating stars that would be ineligible for silicate emission from their spectral type and luminosity class do have such emission. Most noteworthy are the RV Tauri stars. Figure 13 from Gehrz (1972) shows such stars in which dust is unmistakably present. Thus U Mon clearly shows a silicate double hump. The carbon

https://doi.org/10.1017/S0074180900054668 Published online by Cambridge University Press

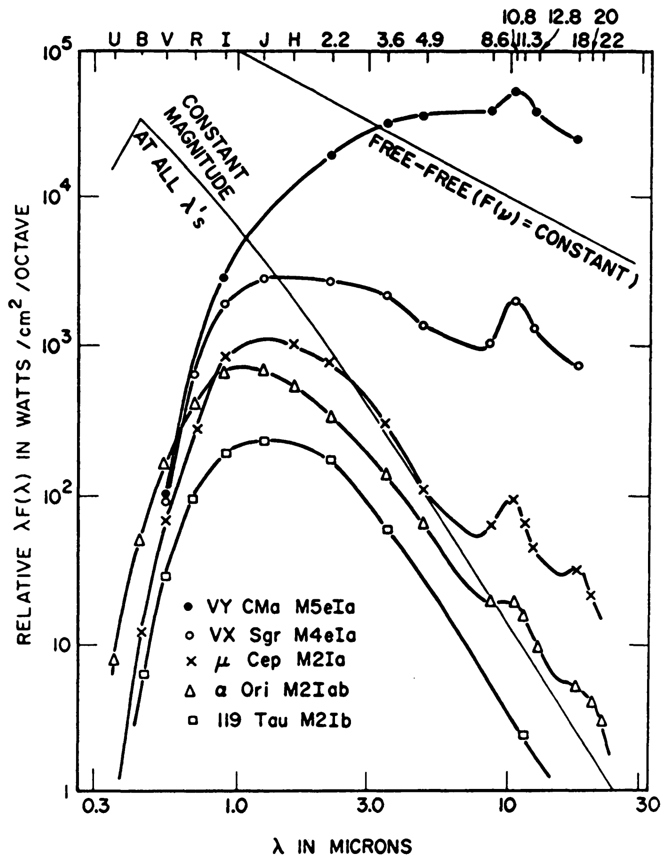

Fig. 12. Photometric measures of M supergiants.

star AC Her shows a spectral distribution that is unique, and the condensate here is unknown.

Other RV Tauri stars show continua that slowly rise to long wavelengths, with little or no spectral evidence near 10 μ of particular solids. It seems more reasonable to assume these are optically thick dust shells rather than that a new class of gaseous continuum should be evoked.

Two carbon rich hydrogen deficient supergiants are known to have excess emission. These are the variable stars R Cr B and RY Sgr. The sudden decline in light of these stars and slower recovery, together with apparent absence of early extinction of chromospheric optical emission lines is good evidence that dust is formed here. The spectra (Stein *et al.*, 1969a; Lee and Feast, 1969) show a smooth black body like continuum temperature $\sim$ 800 K and more detailed observations in the 10 and 20 μ range confirm the smoothness there. For stars like this, the near absence of hydrogen permits carbon to condense at a fairly high temperature, and this is probably the emitting material that is observed.

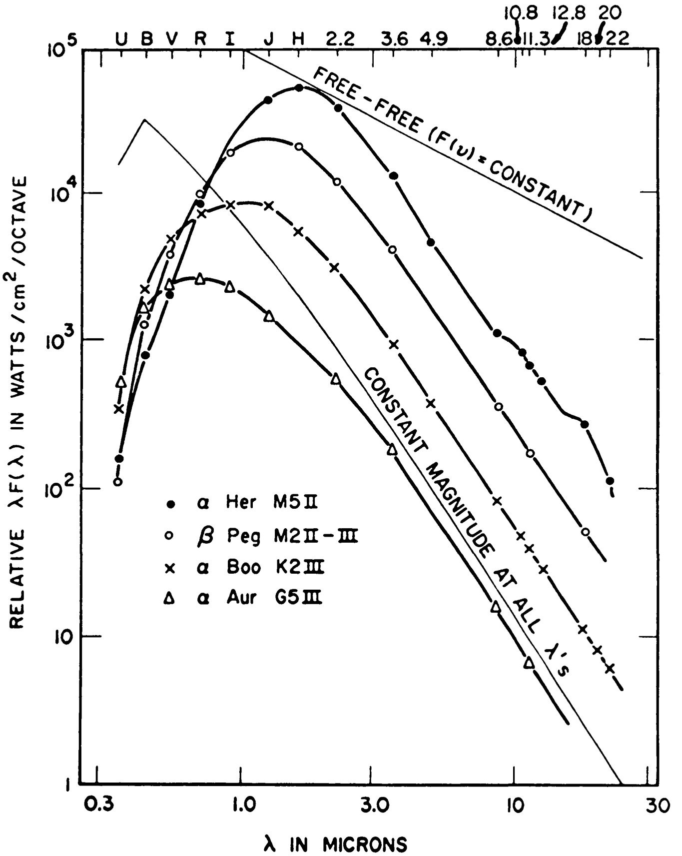

Fig. 13. Photometric measures of RV Tauri stars.

Two somewhat warmer luminous stars are known to also have black body like circumstellar emission. These are 89 Her, F2Ia (Gillett *et al.*, 1970) and the hydrogen deficient A star binary υ Sgr (Lee and Nariai, 1967). For both these stars there seem to be weak emission features at 10 and 20 μ superposed on the black body, indicating that some dielectric solid material is formed. However, there is no certainty for these two stars that the black body $\approx$ 800 K feature is due to solids. Other luminous F supergiants such as ε Aur, F0Ia and ι Sco F2Ia show no excess emission from 3–10 μ. Even a star such as ρ Cas, F8Ia$^+$ that is known to eject matter, currently shows no circumstellar emission.

For 89 Her, the discussion of NGC 7027 and of solar system condensates suggests iron as a more likely condensate than carbon. For υ Sgr both would seem possible.

6. Dust Around Hot Evolved Stars

Hot stars with circumstellar matter generate excess infrared radiation from free-free

https://doi.org/10.1017/S0074180900054668 Published online by Cambridge University Press

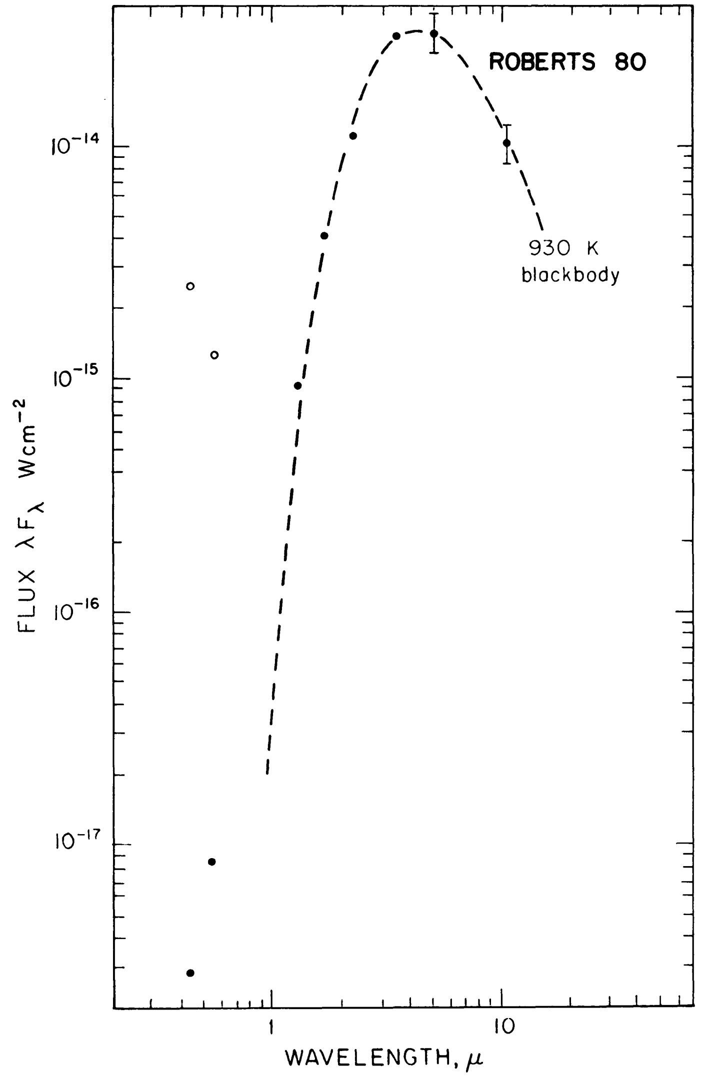

Fig. 14. Photometric measures of the WR star Roberts 80.

and free-bound transition in the matter ionized by the star's light, and/or collisions. However, in some stars there may be excess infrared radiation attributiable to dust. In these cases extreme care must be exercised in insisting that dust is present. Cool black body like emission could also be produced by a dense lightly ionized gas, by electrons scattering off neutral particles (Dyck, private communication).

Two possible cases of time variable dust emission from Be stars were mentioned by Woolf *et al.* (1971). A far better case has been made by Allen *et al.* (1972) for the Wolf-Rayet star Roberts 80, Figure 14. Here a substantial fraction of the star's energy appears to come out as a black body continuum of $T \approx 930$ K.

Other cases of excess infrared continua in Be, P Cygni and WR stars seem more consistent with free-free emission, and in these cases the IR emission can be shown to be consistent with predictions from the optical emission lines.

A number of planetary nebulae show both a cool continuum and some emission lines (Gillett *et al.*, 1972). The emission is spectrally unlike that found in cool M, S or C stars, therefore if it is dust, it would seem to be manufactured *in situ*, perhaps in small condensations embedded in the nebula like raisins in a pudding. There is a similarity between these observations, and observations of H II region in the 100 μ region, (Hoffmann *et al.*, 1971; Harper and Low, 1971) where there seems little possibility of evoking a gaseous continuum. Thus we shall assume that the planetary nebulae condense iron dust as was discussed. Further observations of the semi-sharp 11.3 μ feature reported for NGC 7027 may imply a need to modify this conclusion.

Novae appear to condense dust some weeks after their outburst (Kleinmann, 1972). This is being discussed in another paper at this meeting. The only comment appropriate here is that iron would seem the likely first condensate. Presumably supernovae may also be expected to follow this behavior, though no infrared observations of supernovae have yet been reported, and the time from outburst before dust condenses may be many months, or even years.

7. Evolved Stars; Summary and Conclusions

All of the objects discussed in the sections on evolved stars are known spectroscopically to be ejecting matter. The condensates will become interstellar dust. Therefore, it is of interest to ask which condensates are likely to arise from which stars. Table I below attempts to summarize the discussion above.

8. Solids Around Young Stars and Protostars

When a star is surrounded by circumstellar dust, this is subject to radiation pressure. The dust flows through the gas imparting momentum to it, and typical outflow velocities of 10–100 km s^{-1} are generated. Thus at such speeds the dust moves out a distance of 1 pc in less than 10^5 yr. This naive calculation fails if there is a net inward pressure on the star. This pressure could arise in one of two ways. Condensation of a protostar occurs with the outer layers lagging behind the inner layers. This lag is comparable with the free fall time of the outer layers, and in an initial condensation of density $N_H \approx 10^2$, this phase may last a few million years. In the second case the star may be in a gas flow. For example, if an O star is ionizing a dense cloud of dust and gas from the outside, then the ionized gas will flow back past the star. Dust embedded in the gas would then be brought close to the star.

Both of these processes are probably significant for young stars. The second process probably explains the emission of the trapezium region of the Orion Nebula. Similar spectral features are found in several stars in the Orion nebula (Ney, private communication). They are also seen in the O star Herschel 36 embedded in a dust cloud in M8,

TABLE I
Solids produced by evolved stars

Material	Types of star
Silicates	M and S stars G and K supergiants RV Tauri stars (some) Solar Nebula (meteorites) Comets
Iron	Solar Nebula (meteorites) A and F unusual supergiants[b] Planetary nebulae[b] Be P Cygni and WR stars (some)[b] Novae and supernovae[b]
Carbon	R CrB stars Hot H deficient stars[a] C stars[b]
Si_3N_4	C stars[a]
Unknown dielectrics	RV Tauri stars (some) A and F unusual supergiants Planetary Nebulae[a]

[a] Spectral feature observed, identification in doubt.
[b] Black body like spectra, with negligible evidence for identification.

in CoD 12403 in the same nebula, but not in the O5 star 9 Sgr which is in gas of density 10^2 now. Nor is it seen in S Mon, another early O star mainly free of gas.

It can be predicted in such cases that for a given luminosity star and velocity of flow, the dust stays out to a distance proportional to (gas density)$^{-\frac{1}{2}}$. The temperature of the gas is independent of the luminosity of the star, and is proportional to (gas density)$^{\frac{1}{4}}$. However, if the gas is ionized by UV radiation, it will be optically thick for Lα photons, which will then be absorbed by the dust (Krishna Swamy and O'Dell, 1967). In such cases the dust will be hotter than simple theory predicts. Other such stars with silicate dust around include the two T Tauri stars that flared up, V1057 Cygni (Cohen and Woolf, 1971) and FU Ori (Cohen, private communication).

Stars that probably still have some condensation occurring are the T Tauri stars, particularly the stars in comet shaped nebulae. Incoming matter will bring angular momentum. This will be ejected, with least possible accompanying mass from the outer edge of a disc. The core's light will mainly escape perpendicular to the plane of rotation and illuminate nearby condensations of dust. Since the light escapes along two co-axial opposed cones, this will explain cometary nebulae such as those accompanying R Mon and R Cr A (Mendoza, 1968) or LK Hα101 and T Tauri itself. Since the rotating disks are likely to have a very high density, spectral features from the hot dust should not be apparent. Figure 15 from Gehrz (1972) shows examples of such objects.

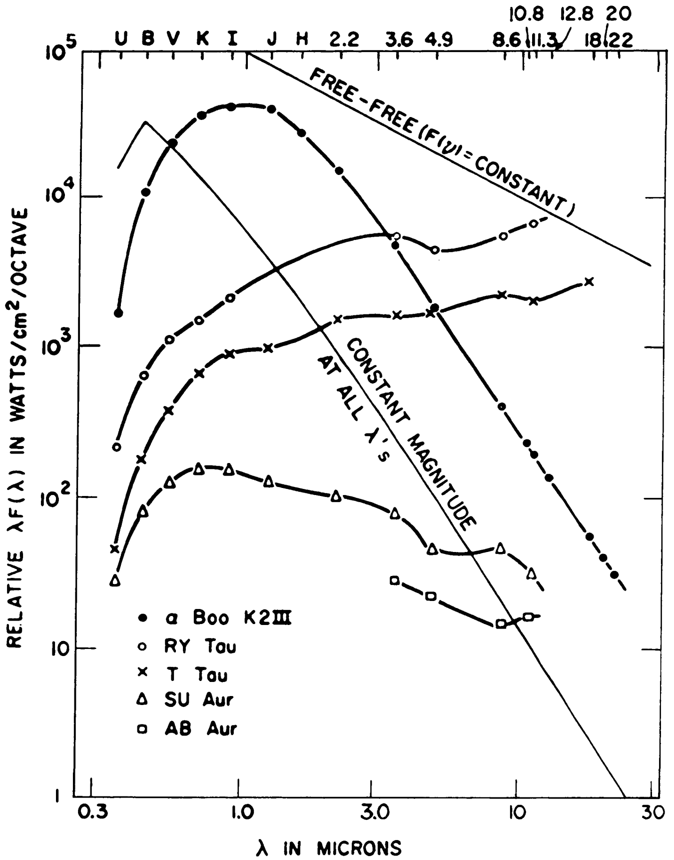

Fig. 15. Photometric measures of T Tauri stars.

Young stars will form from dust and gas as it occurs in space. Some of the matter will fail to condense, and will be returned unchanged to space. Other matter may get close to the star, have molecular bands broken, and perhaps remade. Under such circumstances it is possible that silicates would become iron or gas, or any combination of change between the three might take place. However, it seems that these changes will occur in relatively high density cool places, and so most material that can form non-volatile solids will leave protostars as solids.

Sometimes events may be explosive as in η Carina where matter started moving out in 1843. In the late last century the object changed from a gaseous absorption spectrum to an emission spectrum and slowly dimmed. However, Westphal and Neugebauer (1969) showed that the dimming was probably the result of dust formation, since the IR luminosity now is comparable with the optical luminosity at light maximum. Ney has found the spectrum to resemble a cool black body with a weak silicate feature superposed. The angular structure is resolved on the sky. Here it seems there may have been a substantial conversion from one kind of solid matter into another. By analogy with predictions for novae, etc., we may expect iron to be a major condensate.

In all of these cases, if most potential solids are already condensed, we should not expect much change to result. If more matter forms stars than is ejected directly back into the interstellar medium, then the composition of dust will be determined by processes of star death. On the other hand, if star formation is relatively inefficient, more dust may change its composition through star formation than through star death. Currently it is believed on shaky evidence that the first of these situations holds.

9. Rates of Dust and Gas Ejection from Evolved Stars

Deutsch (1968) estimates that in the solar neighborhood about 4×10^{-10} $M_{\odot}$ per year of dead star matter is returned to the interstellar medium per square parsec of galactic plane. About half of this comes from stars of less than 2 $M_{\odot}$ and half from more massive stars.

Early attempts were made to associate the mass return from low mass stars with ejection from planetary nebulae. These solutions seemed inadequate because planetary nebulae seemed only to contain about 0.1 $M_{\odot}$. Gehrz and Woolf (1971) and Woolf and Pepin (1972) showed that this mass can probably be mainly explained as ejecta from Mira variables. Within tolerable uncertainties, the calculated rates agree with the observations. It seemed in these cases as though all possible silicates were condensed in the ejecta. Thus for this half of the returning mass we may expect 90% of solids to be silicates and perhaps 10% iron.

Studies of mass ejection from stars more massive than 2 $M_{\odot}$ are in a less satisfactory state. Ejection from currently known massive cool M supergiants does not seem to be adequate, perhaps by a factor 10. It is possible that some of the CIT objects represent cool remnants of massive stars, and perhaps these are a significant fraction of objects that return matter. Some carbon stars represent the death of moderately massive stars, and so do some S stars. However, carbon variables are several times as rare as M variables. Thus again it would seem likely that these would only represent perhaps 10% of the ejecta of massive stars.

Then one is left with the possibility that the remainder, less than 80% of the return from high mass stars, comes off as winds from Be and related stars, or in supernova explosions. In such cases the solid ejecta is probably mainly iron.

If we attempt to total these we find the composition of solids entering interstellar space as silicates > 50%, carbon > 5%, iron < 45%, silicon nitride > 1.5%. Such numbers only hint at the results of the detailed study necessary.

10. The Composition of Interstellar Dust

Current estimates of star formation rates and of star deaths are the same, implying that the fraction of the Galaxy as interstellar medium is not changing rapidly with time. However, both of these numbers are small compared with the current mass of the interstellar medium, and imply change only on a cosmological time scale. Thus although we know a little about the way dust now enters the interstellar medium, we do not know whether this entering matter is similar to the matter now there.

It seems highly unlikely that the interstellar medium is primordial. Heavy element abundances seem if anything higher than in the Sun. Therefore if the medium started as hydrogen, with perhaps helium, it has been processed through being a star at least once. Our possible doubts about the current composition of dust arise because we do not know what these early stars were, or how they died. We only know that they emitted copious amounts of heavy elements. Fortunately, the discussion we have just been through about ejecta from stars suggests that in all such cases solids do condense, and the main uncertainty is the fraction of the matter ejected as silicates, and as iron. Here the observations of the Orion nebula in Figure 1 are of paramount importance. Silicates are obviously present. There is no sign of a hot black body continuum to signify the presence of iron or carbon. The Orion nebula is presumably a typical sample of the interstellar medium.

The next question is, are there mantles on the solid matter? Here we have observations of two dusty regions, one in the Orion Nebula, the other in the galactic center. Water ice may be present, but only represents about 10% by mass of the silicate matter in the line of sight to these objects. The long searches by Knacke *et al.* for the 3.1 ice band show that though ice mantles may exist in some places, they are a rarity.

Finally therefore we can try to estimate the amount of interstellar silicate. From the observation of the Orion star, and the negative evidence of VI Cygni #12 and HD 168625, the ratio of interstellar visual extinction to silicates 9.7 μ extinction is $\approx$ 50:1. Thus we find that there are 6×10^{-26} to 2×10^{-25} g of silicates per magnitude of interstellar absorption. Such absorption is probably associated with 2.5 to 5×10^{-3} g of interstellar gas. This implies a mass ratio of silicates to gas of between 1:125 to 1:800. These ratios must be decreased, by perhaps 10% to allow for ice, and at least a further 10% to allow for carbon, iron, silicon nitride etc. to obtain the ratio of total solids to gas.

If we assume an actual ratio of 1:250 then most silicon, iron, aluminum, magnesium, and calcium would be locked into the dust. Some problems of curiously low cosmic abundances of these materials in the interstellar gas would then have been explained. Again, factor of two uncertainties in cosmic compositions make the appropriate gas to dust ratios uncertain. However, we may now invert the abundance argument, and suggest that most matter condensable into nonvolatile silicates exists in that form.

It is up to us to then use the interstellar extinction curve to infer what these cosmic abundances are. Some difficulties of interpretation will arise because cosmic ray and low energy proton bombardment fracture bonds, and make the optical properties of the material anomalous. However, almost regardless of these problems it seems that the interstellar dust needs to be about 1% of the gas by mass, and this does seem to be possible if the bulk of the dust is silicates that condensed in cool stellar atmospheres.

Acknowledgements

This article could not have been written without many discussions with almost all active infrared observers. However, special acknowledgements go to Dr F. C. Gillett without whose work this paper would have had a different form, and some erroneous conclusions. The research has been supported by the National Science Foundation under grants GP-27983 and GP-32772.

References

Allen, D. A., Harvey, P. M., and Swings, J. P.: 1972, *Astron. Astrophys.*, **20**, 333.
Becklin, E. E. and Westphal, J. A.: 1966, *Astrophys. J.* **145**, 445.
Becklin, E. E. and Neugebauer, G.: 1968, *Astrophys. J.* **151**, 145.
Cohen, M. and Woolf, N. J.: 1971, *Astrophys. J.* **169**, 543.
Danielson, R. E., Woolf, N. J., and Gaustad, J. E.: 1965, *Astrophys. J.* **141**, 116.
Davies, R. D., Masheder, M. R., and Booth, R. S.: 1972, *Nature* **237**, 21.
Delmer, T. N., Gould, R. J., and Ramsay, W.: 1967, *Astrophys. J.* **147**, 495.
Deutsch, A. J.: 1956, *Astrophys. J.* **123**, 210.
Deutsch, A. J.: 1968, in M. Hack (ed.), *Mass Loss from Stars*, Reidel Publ. Co., Dordrecht, p. 1.
Gehrz, R. D.: 1972, Thesis, University of Minnesota, Minneapolis.
Gehrz, R. D.: 1971, *Bull. Am. Astron. Soc.* **3**, 454.
Gehrz, R. D. and Woolf, N. J.: 1971, *Astrophys. J.* **165**, 285.
Gillett, F. C., Low, F. J., and Stein, W. A.: 1967, *Astrophys. J.* **149**, L97.
Sillett, F. C., Low, F. J., and Stein, W. A.: 1968, *Astrophys. J.* **154**, 677.
Gillett, F. C., Hyland, A. R., and Stein, W. A.: 1970, *Astrophys. J.* **161**, L219.
Gillett, F. C., Merrill, K. M., and Stein, W. A.: 1972, *Astrophys. J.* **172**, 367.
Hackwell, J. A.: 1971a, *Observatory* **91**, 37.
Hackwell, J. A.: 1971b, Thesis, London University College.
Hackwell, J. A., Gehrz, R. D., and Woolf, N. J.: 1970, *Nature* **227**, 822.
Harper, D. A. and Low, F. J.: 1971, *Astrophys. J.* **165**, L9.
Hoffmann, W. F., Frederick, C. L., and Emery, R. J.: 1971, *Astrophys. J.* **170**, L89.
Humphreys, R. M., Strecker, D. W., and Ney, E. P.: 1971, *Astrophys. J.* **172**, 75.
Kleinmann, S. L.: 1972, Thesis, Rice University.
Knacke, R. F., Cudaback, D., and Gaustad, J. E.: 1969, *Astrophys. J.* **158**, 151.
Krishna Swamy, K. S. and O'Dell, R. C.: 1967, *Astrophys. J.* **147**, 529.
Lee, T. A. and Nariai, K.: 1967, *Astrophys. J.* **149**, L93.
Lee, T. A. and Feast, M. W.: 1969, *Astrophys. J.* **157**, L173.
Low, F. J., Kleinmann, D. E., Forbes, F. F., and Aumann, H. H.: 1969, *Astrophys. J.* **157**, L97.
Low, F. J., Johnson, H. L., Kleinmann, D. E., Latham, A. S., and Geisel, S. L.: 1970, *Astrophys. J.* **160**, 531.
Maas, R. W., Ney, E. P., and Woolf, N. J.: 1970, *Astrophys. J.* **160**, L101.
Mendoza, E. E.: 1968, *Astrophys. J.* **151**, 977.
Neugebauer, G. and Leighton, R. B.: 1969, *Two Micron Sky Survey: A Preliminary Catalog*, NASA, Washington, D.C.
Neugebauer, G., Becklin, E. E., and Hyland, A. R.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 67–102.
Ney, E. P. and Allen, D. A.: 1969, *Astrophys. J.* **155**, L193.
Stein, W. A., Gaustad, J. E., Gillett, F. C., and Knacke, R. F.: 1969a, *Astrophys. J.* **155**, L3.
Stein, W. A., Gaustad, J. E., Sillett, F. C., and Knacke, R. F.: 1969b, *Astrophys. J.* **155**, L177.
Stein, W. A. and Gillett, F. C.: 1971, *Nature* **233**, 72.
Toombs, R. I., Becklin, E. E., Frogel, J. A., Law, S. K., Porter, F. C., and Westphal, J. A.: 1972, *Astrophys. J.* **173**, L71.
Westphal, J. A. and Neugebauer, G.: 1969, *Astrophys. J.* **156**, L45.
Woolf, N. J.: 1971, *Mem. Soc. Roy. Sci. Liège* **6**, III, 205.
Woolf, N. J. and Ney, E. P.: 1969, *Astrophys. J.* **155**, L181.
Woolf, N. J., Strittmatter, P. S., and Stein, W. A.: 1970, *Astron. Astrophys.* **9**, 252.
Woolf, N. J. and Pepin, T. J.: 1972, unpublished.