Session VIII

CIRCUMSTELLAR SHELLS

Participants reclining on the 1850-year-old stone seats of the theater at Aspendos, watching nothing in particular.

CIRCUMSTELLAR DUST AROUND M, S AND C STARS

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Abstract. The circumstellar shells of M stars produce emission features due to amorphous silicates peaking around 10 and 18 μm, with additional emission at 11 μm due to crystalline olivine and at 13.1 μm (unknown carrier). C stars are associated with SiC dust emission at 11.2 μm with additional emission around 8.9 μm, whereas S stars have a relatively weak 10.5 μm emission feature which is due neither to silicates nor to SiC.

1. Introduction

With the advent of IRAS a new episode of infrared astronomy began with the identification of hundreds of thousands of infrared sources. Thousands of these sources were bright enough (>2 Jansky) to have their spectra recorded in the 8–22 μm region with the Low Resolution Spectrometer (LRS). This wavelength region is rich with different types of dust emission features. The existence of dust in circumstellar envelopes has been known for many decades. Stars on the AGB eject copious quantities of gas into space, part of which will condense into solid grains after the gas has cooled to $T < 1500\,K$. The type of grain that is produced depends on the composition of the out-flowing material. In the oxygen-rich shells ($C/O < 1$) that are associated with M stars, the oxygen remaining after the formation of CO will condense into oxygen-rich solids such as amorphous silicates with emission features around 10 and 18 μm. On the other hand, in the carbon-rich shells ($C/O > 1$) associated with C stars, the extra carbon will condense into SiC grains with an emission feature around 11.2 μm.

IRAS was very good in characterizing large numbers of LRS by their major emission and absorption features. However, noisy spectra at times were assigned incorrect characterizations and previously unknown features could not be accommodated by the classification scheme.

R.F. Wing (ed.), The Carbon Star Phenomenon, 361-366.

2. The M stars

In 1990, Little-Marenin and Little (LML90) analyzed IRAS LRS spectra of Mira variables and showed that the 10 μm silicate emission feature (called class Sil) showed additional dust components at 11 μm (crystalline olivine; class Sil+) and at 13.1 μm (class 3C). The carrier of the 13.1 μm feature has not yet been unambiguously identified, but it does not appear to match the characteristics of corundum (Sloan et al. 1996). The strength of the 11 μm feature at times rivaled or surpassed the strength of the 10 μm feature (class Sil++). A weak, broad feature extending from 9 to 15 μm was also identified, possibly due to aluminum oxide. Besides the 10 μm feature, amorphous silicate has a long-wavelength feature that peaks at 18 μm. In stars which show Sil+ and 3C features, we found that the long-wavelength feature peaks at 19 μm rather than at 18 μm.

Two recent studies (Hron et al. 1997; Sloan & Price 1995) have done much to quantify the characteristics of the different types of dust emission seen in M stars. The two methods emphasize different aspects of the emission. Sloan and Price wanted to investigate correlations between the total amount of dust emission and the shape of the emission longward of 10 μm by using the flux ratios F_{10}/F_{11} and F_{11}/F_{12}. They showed that the total dust emission in M stars is constrained to a narrow sequence of shapes ranging from the classic narrow feature peaking around 10 μm to the broad, low-contrast feature which peaks between 11 and 12 μm. They use this sequence to classify emission features of AGB stars. The LML90 classes more or less fall in different segments of their distribution. A limitation of their method is that they only used the longward portion of the emission features, whereas there are clear differences in the shape of the various classes that can be identified shortward of 10 μm.

Hron et al. on the other hand concentrated on investigating the shapes of the emission features by first subtracting a photospheric and dust "continuum" from the LRS. Using ratios of the remaining integrated flux in both the short- and long-wavelength portion of the feature, they found that they could recover the various LML90 classes. Their analysis showed that Miras on average tend to have thicker shells and stronger features than semiregular variables (SRb). It is unclear if their conclusion that Miras have lower stellar temperatures is not an artifact of their method. The 13.1 μm component appears to be associated primarily with SRb variables and with a fairly narrow range of shell optical depth. Sloan et al. (1996) also found that the 13.1 μm feature is associated primarily with SRb variables and occurs in approximately 75–90 % of these sources.

At large optical depths in the shell, the silicate features go into absorption. It is easy to confuse a partially self-absorbed silicate feature seen in

M stars with the SiC plus 8–9 μm feature seen in C stars, as has been done in several papers in the literature.

A few AGB stars show no dust emission features.

3. The C Stars

The circumstellar shells of many C stars are characterized by SiC dust emission at 11.2 μm. Unlike the 10 μm silicate feature, we found the SiC feature to be so uniform that it could be used for classification purposes (Little-Marenin et al. 1987). In a few stars (Y CVn, RY Dra, IRC+10216) the SiC feature is shifted so that it peaks at 11.4 μm.

We (Little-Marenin et al. 2000) and Goebel et al. (1995) have identified an emission feature in the 8−9 μm region possibly due to a:C−H, as well as absorption in the 13−15 μm region due to C_2H_2 and HCN. A few stars show a weak, broad emission feature which is clearly different in shape from the aluminum oxide feature seen in M stars. Its carrier has not as yet been identified.

After removing an estimated stellar contribution, we find that the majority of our sources fall into two categories: spectra with the classic SiC emission feature peaking around 11.2−11.5 μm (we will call this class SiC), and spectra where the SiC feature appears along with an additional component peaking around 8.5–9.0 μm (class SiC+). In a few stars the 8−9 μm feature rivals or exceeds the SiC feature in strength (class SiC++).

The classic SiC class contains mostly Mira variables, while the SiC+ and SiC++ classes contain mostly semi-regular and irregular variables. The periods of the classic SiC sources are longer than those of the SiC+ sources; that is true for both the Miras and the SRb variables. Classic SiC sources tend to have slightly redder [12]−[25] colors and correspondingly lower photospheric temperatures than the SiC+ and SiC++ sources. The classic SiC feature appears to be superimposed on a featureless continuum most likely due to amorphous carbon or graphitic material and is strongest for Miras. The C/O ratio increases along the sequence (SiC) → (SiC+) → (SiC++) from an average of 1.07 (SiC) to 1.2 (SiC+) to 1.3 (SiC++). Assuming that a:C−H is the carrier of the 8−9 μm feature (Goebel et al. 1995), we propose that this feature will strengthen with increasing C/O ratio. Support for this suggestion can be found in the increasing strength of the C_2H_2+HCN absorption feature seen in the 13−15 μm region and in the spectrum of VX And which has the largest C/O ratio (1.76) and the strongest contribution from the 8 − 9 μm feature.

Our sample of 99 stars was selected by cross-referencing the IRAS *Point Source Catalog* and the *General Catalogue of Variable Stars*. Four sources show no dust emission, 8 have a weak, broad feature that is difficult to classify, and 5 of these sources show emission from oxygen-rich dust, including two well-known silicate–carbon stars (BM Gem and V778 Cyg), and two S or SC stars which have been classified at various times as carbon stars (S Lyr and ST Cam). On the other hand, NP Pup appears to be related to the CS stars (Bidelman, private communication).

4. The S Stars

Pure S stars with C/O close to unity show an emission feature peaking around 10.5 μm which is subtly different from the 10 μm amorphous silicate or the 11.2 μm SiC feature (Little-Marenin & Little 1988). Neither Hron et al. (1997) nor Sloan & Price (1995) were able to clearly distinguish this S-star feature from other emission features by their methods. A direct superposition of the spectral shapes of the various emission features is needed.

In general S stars tend to have lower mass-loss rates and higher gas-to-dust ratios than M or C stars, implying less efficient dust formation in their circumstellar shells (Bieging & Latter 1994). Gas-to-dust ratios are estimated to be between 400 and 1000, at least a factor of two higher than for carbon stars, and hence strong dust emission features are not seen or expected.

I have identified seven S stars listed in the catalogue of Chen et al. (1995) which are listed as having very strong silicate features at 10 and 18 μm in their IRAS LRS spectra (LRS 25–29): IRAS 07197−1451 = TT CMa; 11169−6111; 15347−5555; 16490−4618; 19545−1122 = V1407 Aql; 21029+4917; and 22512+6100 = V386 Cep. However, all seven stars are actually either M or MS stars rather than pure S stars (Little-Marenin 2000), and hence they reflect the mass-loss rates and dust content associated with M stars.

I suggest that among true S stars we should find a few stars with strong 10 μm silicate features and enhanced ^{13}C content with ^{12}C/^{13}C ratios near the CNO equilibrium value of 3.4 rather than having values around 20, typical for S stars. If these stars are found they could be precursors to the Silicate–Carbon stars (Little-Marenin 1986), possibly produced by a helium core flash. However, no consensus about the evolutionary status of the Silicate–Carbon stars exists as yet. The MS stars with strong silicate features may fall into this category since all other MS stars I have analyzed have only weak silicate emission features. But no enhancement of ^{13}C has yet been identified (or searched for) in these stars.

The spectra of carbon-rich proto-planetary nebulae show an emission feature around 21 μm.

5. Conclusion

Dust emission from circumstellar shells of AGB stars shows a variety of features in the 8–22 μm region. Besides the 10 and 18 μm amorphous silicate features, M stars have additional emission at 11 μm (crystalline olivine) and at 13.1 μm (unknown carrier), as well as a broad, low-contrast feature (9–15 μm) probably due to aluminum oxide. Most C stars show the classic SiC feature (11.2 μm), but many also show an 8–9 μm emission feature that strengthens with increasing C/O ratio. A featureless continuum (amorphous carbon or graphitic material) underlies the emission features. The S star feature peaking around 10.5 μm is difficult to identify except by directly comparing its shape to other emission features. A number of AGB stars show no dust emission. It has been suggested that the 11.3 μm feature superimposed on the amorphous silicate feature seen in some supergiants is due to PAHs rather than crystalline olivine. This finding is very interesting but needs further verification.

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Discussion

Elitzur: Extracting spectral features by subtracting a single-temperature blackbody is a dangerous procedure. The correct analysis must involve a full radiative transfer calculation in which the dust opacity, including features, is an input. Detailed results obtained otherwise cannot be trusted.

Little-Marenin: I agree that the best procedure for analyzing the low-resolution spectra is a full radiative transfer calculation, but my simple subtraction of a blackbody allows one to identify different dust components.

[Unknown]: Why would you expect less dust emission at maximum light than at minimum?

Little-Marenin: At higher luminosity and temperature, the condensation radius should move outward, evaporating grains, while at minimum the dust grain radius moves inward creating larger amounts of dust.

Ivezić: I would like to comment on the "discrepancy" between the behavior of the light curve and the strength of the 10 μm silicate feature. It is true that the optical depth should be larger during minimum light, but the strength of the feature can both decrease and increase with optical depth. Therefore, as the luminosity of the star changes, the feature strength can either increase or decrease.

Little-Marenin: Good.

Speck: The shift of the SiC peak from 11.2 to 11.4 μm was attributed to a change from α–SiC to β–SiC. However, the β–SiC feature peaks at a shorter wavelength than α–SiC, so this is unlikely. On the other hand, impurities in α–SiC shift the peak to longer wavelength. My own work on the 8.6–8.9 μm feature suggests that there is no trend with optical depth. Maybe this suggests no evolutionary trend in the 8.6–8.9 μm feature.

Little-Marenin: Thank you for the information on α– and β–SiC. We find trends in the strength of the 8.9 μm feature with varying C/O, but like you, we find no correlation with optical depth.

van der Bliek: The IRAS LRS spectra were calibrated using the spectrum of α Tau. However, the LRS spectrum of α Tau turned out to have an SiO absorption feature (7–10 μm), and this absorption then shows up as an "emission feature" in spectra without SiO absorption (Cohen et al. 1992, *AJ*, 104, 2030). Did you correct for this?

Little-Marenin: I corrected all the LRS spectra *à la* Cohen et al. (1992) and rescaled the spectra to the 12 μm PSC fluxes for that date.