WHAT KINDS OF DUST EXIST IN CIRCUMSTELLAR SHELLS OF MIRAS?

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Presented at the AAVSO Session on Mira Stars (part of the 85th Annual Meeting), November 1, 1996

Abstract

Mira variables lose mass which slowly expands into a circumstellar shell surrounding the star. Dust forms in the shell by condensation as the shell cools. The presence of dust is detected by infrared (IR) observations that record the general infrared emission from the cooler dust, as well as by IR spectral scans that detect emission features from the dust. These scans have revealed that the composition of dust in both oxygen- and carbon-rich stars is produced by a larger variety of dust grains than had been anticipated, and that the dust shows variation in phase with the visual light curve.

1. What are Mira variable stars?

Stars spend most of their lives on the main sequence, changing little as they slowly convert hydrogen into helium in their cores, thereby releasing energy by nuclear fusion. When the hydrogen is exhausted in their cores, the low mass stars begin to brighten and become larger in radius, thereby making their ascent up the red giant branch. At the tip of the giant branch, their previously inert cores of helium begin the fusion reaction of helium into carbon, and the stars lose some brightness and shrink to the horizontal branch. After the core helium is exhausted, the stars resume a second giant branch ascent with two shells, one of helium and one of hydrogen, surrounding the core of carbon and oxygen. This asymptotic giant branch (AGB) parallels the first giant branch, but the stars in it eventually become even more luminous and larger than before. Stars at the top of the AGB are typically 1–2 AU (100–200 $R_\odot$) in radius and are 2500–6000 times as bright as the sun. They are usually pulsating with periods of 100–400 days and have intervals of thermal pulsing (when the helium shell ignites explosively) on the order of every 10,000 years (Habing 1996). The highest-luminosity part of the AGB is where we find Mira variables and their associated types of stars, the semiregular SRa and SRb variables. Stars whose visual magnitude varies by more than 2.5 magnitudes are called Mira variables, and those with smaller amplitudes are SRa and SRb variables. These variables are thought to be mostly stars of 1–2 $M_\odot$, since the lower mass range has the largest number of stars in it. None of these stars vary as precisely as highly regular variables such as the Cepheids or RR Lyrae stars, and some have a very erratic variation, with both period and amplitude of variation changing from cycle to cycle.

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2. Processes that lead to mass-loss in Miras

Consider the effects of such catastrophic increases in radius and luminosity on the outer edges of the photosphere of these stars: the escape velocity has become very low, the temperature at the edge of the atmosphere is only about 2500 K, and the atmospheric structure is allowing gases to leak away into space. The exact mechanism causing this escape is not well established at present, but it appears to be related to shock waves moving through the star and the presence of convection in the atmospheres of the stars. The escaping gases cool as they expand outward and reach the condensation temperature of dust grains only 2–6 AU from the star. The radiation streaming from the stars is so intense that it exerts a strong outward push on the dust grains when they absorb the radiation. If there is enough dust present (which means that there is enough mass lost by the star per year), then the dust will interact by friction with the gases present to give the entire layer an outward velocity of 10–20 km/sec so that it escapes slowly from the star. (Dust condensed out of the gas makes up only a fraction of one percent by mass of the total material.) Therefore, the dust content of the developing circumstellar shell is very critical to the process of mass-loss and the eventual development of a dust cloud around the star. The dust lost from circumstellar shells is the source of most of the dust found in the interstellar medium, as has been shown by recent studies of meteorites.

3. Detection of circumstellar dust shells

The easiest way to detect the presence of excess dust around a star is to measure the infrared (IR) energy the star is emitting. If there is an excess amount of IR, more than we believe the photosphere of the star should be emitting, then it is probably due to the absorption of the starlight by the dust, and the subsequent re-emission of IR radiation by the warm dust. From our data we deduce that most of the IR emission in the 10 μm region comes from dust with temperatures of 300–900 K. Since the dust is cooler than the photosphere it will emit IR radiation further into the infrared and will show a "hump" of excess emission (see Figure 1).

The IRAS satellite measured the IR emissions of about 250,000 stars at four IR wavelengths. These data are invaluable for showing the presence of excess IR emission. The IRAS satellite also had a low resolution IR spectrometer (LRS) that took 50,000 spectra of the brightest sources between 8 and 22 μm. The LRS spectra help us identify specific dust components that are present in circumstellar shells by looking at discrete emission features in the spectra caused by the molecular structure of the dust grains (see Figure 1). We have studied these emission features in detail. They are caused by the bending and stretching modes of the specific components found in different types of dust grains. They also give us information about their sizes: they are all very small, less than 1 μm. The composition of the material lost from the photosphere determines the type of feature that is seen: stars of normal composition (M stars) have more oxygen than carbon in their atmospheres, and they show the emission feature of dirty silicates (SiO contaminated with Fe, Mg, and Al). The carbon stars (C stars) have extra carbon mixed into their photospheres. Helium fusion reactions in the helium-burning shell make the extra carbon which is mixed outward to contaminate the star's envelope. When carbon exceeds oxygen in abundance, the dust grains are made of graphite or amorphous carbon and silicon carbide (SiC). Silicates have emission features at 10 μm and 18 μm, while SiC has a feature at 11.2 μm, and this gives us a clear way to distinguish carbon star dust shells from normal (oxygen-dominated) ones. Figure 1 shows the spectrum of the unusual carbon star V778 Cyg, which has a carbon-rich photosphere, but shows emission from oxygen-rich dust in its circumstellar shell.

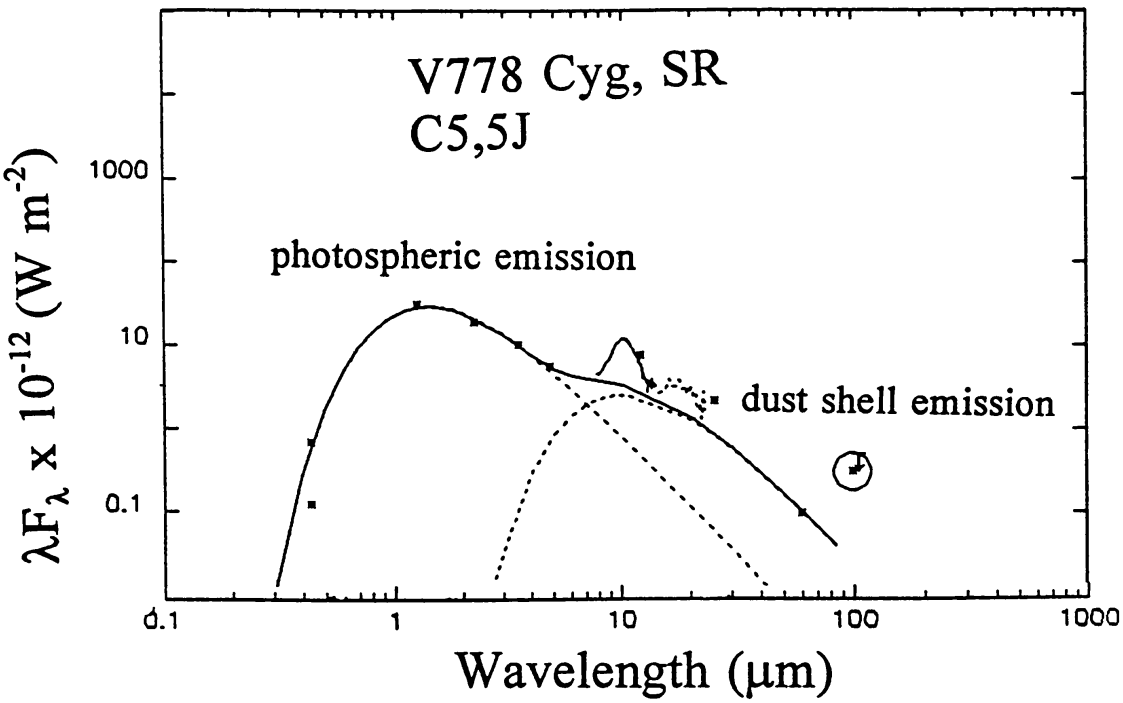

Figure 1. The observed visual, infrared and IRAS fluxes from the carbon star V778 Cyg are fit with two energy distributions. The first one for T = 2650 K represents the photospheric emission from the star and the second one for T = 375 K represents the emission from the dust shell. The emission features from silicate dust at 10 and 18 μm are clearly visible. The point at 100 microns shows contamination by interstellar cirrus.

Detailed analysis of the LRS emission spectra obtained by IRAS of Mira variables allows us to identify six different types of oxygen-rich dust (Little-Marenin and Little 1988, 1990), which are shown in Figure 2. In order to study the dust emission features, we subtracted the photospheric energy emission from the observed spectrum. The most common and strongest features are produced by the stretching and bending modes of SiO at 10 and 18 μm. Less commonly, we see a feature around 11 μm estimated to be produced by crystalline olivine (a type of silicate dust). A relatively weak feature around 13.1 μm has as yet no identified carrier (Sloan *et al.* 1996). A broad emission feature in the 9–15 μm region seen in optically thinner and hotter circumstellar shells has been associated with aluminum oxide grains. Stencel *et al.* (1990) suggest that the different types of dust represent an evolutionary sequence as dust shells become optically thicker with time.

Similar analyses of carbon-rich dust (after subtracting the stellar photospheric emission) shows that the most common dust grain emission feature is produced by SiC (Figure 3). In about 40% of the spectra we have been able to identify an emission feature around 8.5–9 μm, probably produced by a C-H bond believed to be a pre-cursor of amorphous carbon or graphitic dust. The 8.5–9 μm feature tends to be absent in Miras but can dominate the emission from some semiregular variables. The strength of the feature increases with an increasing amount of carbon in the atmosphere and appears to dominate the emission if the carbon/oxygen ratio is larger than about 1.4. The average carbon-rich dust emission features that we have identified are shown in Figure 4 (Sloan *et al.* 1998; contains more precise definitions of the classes).

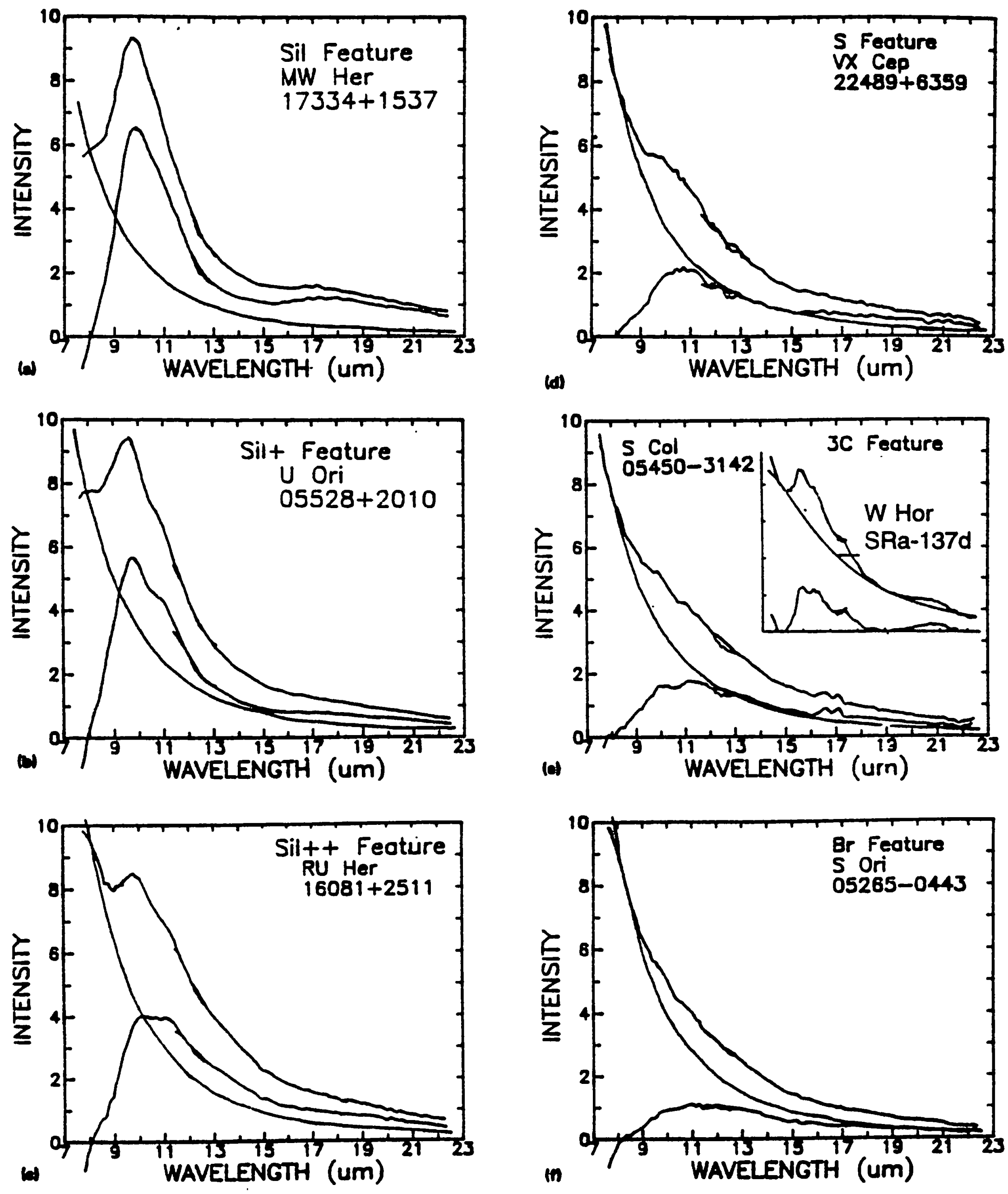

Figure 2. Typical spectra representative of the six types of emission features found in Mira spectra. For each, we plot the observed LRS spectrum and a smooth 2500 K blackbody energy distribution matched to the stellar spectrum at 8 µm. The difference between the observed and blackbody spectrum is plotted above the wavelength scale. (a) shows the typical 10 and 18 µm amorphous silicate emission; (b) shows stars with a contribution of crystalline olivine at 11 µm; in (c), the crystalline olivine feature is as strong as the amorphous silicate feature; (d) shows the feature seen in S stars; (e) shows a three-component feature with maxima at 10, 11, and 13.1 µm; (f) shows a broad feature possibly due to aluminum oxide.

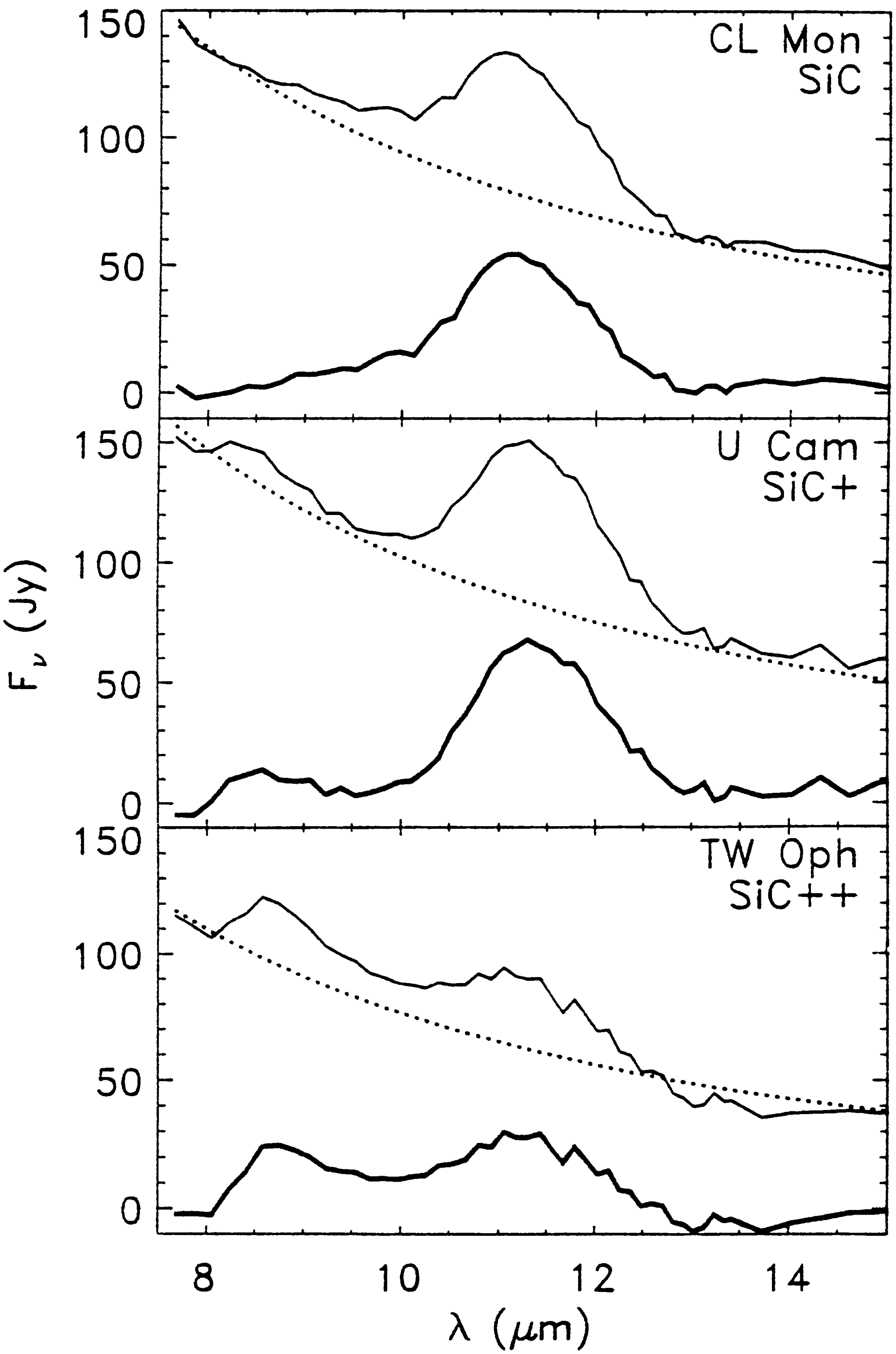

Figure 3. Carbon star LRS spectra in the 8–15 µm region. As in Figure 2, we subtracted a black body energy distribution (dotted line) from the observed LRS spectrum. The difference spectrum (observed minus blackbody spectrum) is plotted above the wavelength axis. The SiC feature at 11.2 µm is clearly visible. A feature in the 8–9 µm region is strong in TW Oph and is associated with the increased carbon abundance in the star.

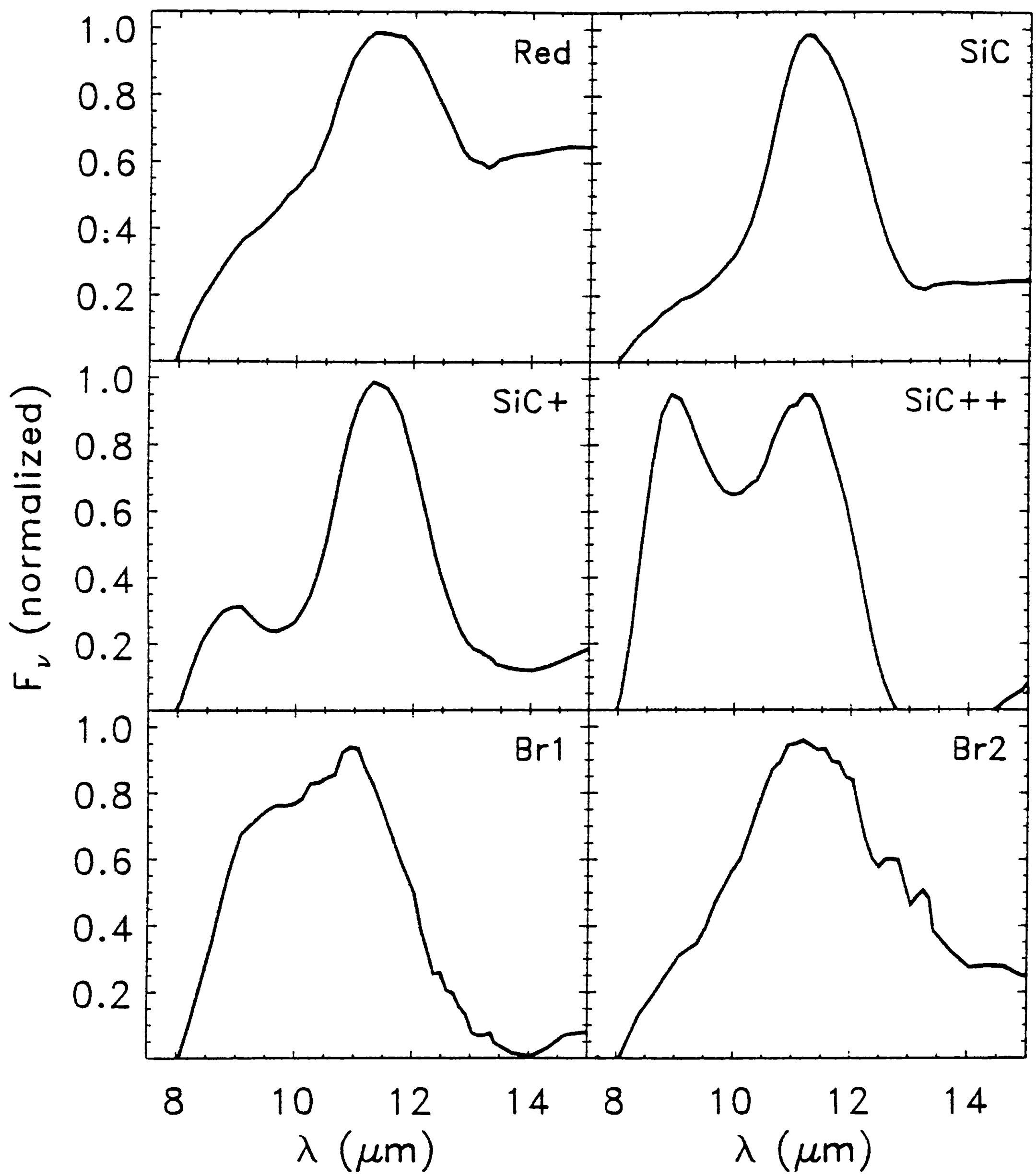

Figure 4. Six types of dust grain features we have been able to identify in carbon stars. The carriers of the Br1 and Br2 features have not yet been identified. See Sloan *et al.* 1998 for more precise definitions of the classes.

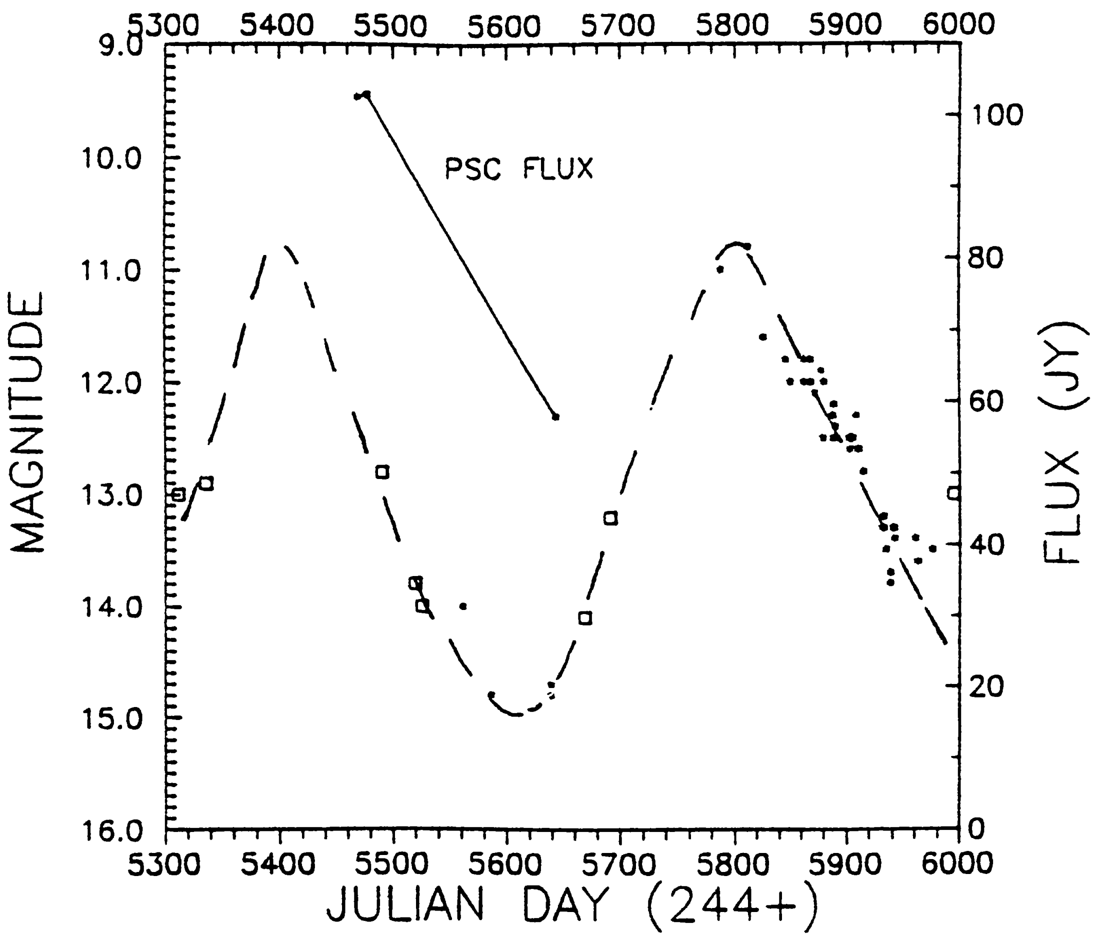

Figure 5. The AAVSO light curve for AU Cyg in 1983, together with the IRAS point source fluxes. These IRAS fluxes clearly vary in phase with the visual light curve. In the AAVSO data, dots are individual positive observations, and open squares are negative (fainter-than) observations.

We have studied some peculiar stars: the S stars and the silicate-carbon stars. The S stars have carbon and oxygen in nearly equal amounts, and they show the augmented presence of heavy elements such as strontium, zirconium, yttrium, and the radioactive element technetium (Little *et al.* 1987). All these heavy elements are made in the helium burning shell during thermal pulses and are mixed into the atmosphere along with the carbon. The spectral emission feature of the S stars is a strange feature located between 10 and 11 μm, but it is neither a silicate nor an SiC emission (see Figure 2d). Its carrier remains unidentified.

The silicate-carbon stars show the silicate emission feature common to oxygen-dominated stars, but they have a carbon-rich photosphere underneath and hence are classified as C stars (Little-Marenin 1986). Figure 1 shows the spectrum of the silicate-carbon star V778 Cyg. Strangely enough, these stars are also members of a group of carbon stars called "J" stars, which have a much larger fraction of the carbon 13 isotope in their atmosphere. The only known manner of enriching a star in carbon 13 is to have a large fraction of the envelope go through partial carbon-cycle hydrogen burning. This could occur if some event (a helium core flash at the tip of the Red Giant

Branch?) mixed the envelope of the star with the core. The only (but not totally successful) explanation advanced is that the silicate carbon stars may be members of a binary system.

Maser emission from molecules in the circumstellar shell has also been observed, and it confirms that stars are losing mass at a low velocity. Measurements of molecular CO microwave emission lines also confirm this fact.

4. Effect of variability on the circumstellar dust shell

We know that maser emission varies during the variability phase of the star. Maser emission is observed from the earth's surface, and can be monitored easily given enough radio telescope time. Comparing the water maser emission with the visual light curve from the AAVSO clearly shows that the two correlate (Benson *et al.* 1992), but we have observed that the maximum of the maser emission is delayed by about 20% of the phase behind the visual emission maximum.

The IRAS satellite was functioning in orbit for about 11 months in 1983, but it was able to observe the same part of the sky only twice during that time. We have shown from IRAS spectra that there is some variation in the strength of the emission feature during the variation cycle, and that there is a slight change in the IR emission excess from the dust as seen in the Mira variable AU Cygni (Figure 5). When we have good observations from the AAVSO for these stars, we can determine when the maximum emission in the visual occurs, and we can get the period of emission and the phase of the light curve as a function of the date (Little-Marenin *et al.* 1996). The IR emission features may also show a phase lag, but the data are much more difficult to interpret since there has been no consistent source of IR spectra since IRAS.

Observations of mass-loss rates have not revealed any variation with the phase of the visual light curve, but this would be difficult to establish since mass-loss cannot be very accurately measured.

Acknowledgement

Without AAVSO data for the stars we have studied, we could not have begun the interpretation of these variability data. Our thanks to all AAVSO observers for their assistance in reporting their visual data to the AAVSO.

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