VARIABLE DUST FEATURES IN INFRARED SPECTRA OF AU CYGNI

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ABSTRACT

We report the first clear evidence for variation in the infrared spectral features due to silicates in the circumstellar shell of the oxygen-rich Mira variable AU Cygni, based on individual scans obtained with the IRAS low-resolution spectrometer, during the 1983 IRAS mission. For the optically thin shell of AU Cyg, the contrast of the silicate feature is stronger near optical maximum and weaker near optical minimum. We propose that circumstellar dust has a significant population of small grains. This population may get enhanced near maximum, probably due to evaporation of larger grains, increasing the amount of 10 μm band emission relative to continuum emission. The shape of the emission feature does not vary measurably from maximum to minimum brightness.

Subject headings: circumstellar matter — dust, extinction — infrared: stars — stars: individual (AU Cygni)

1. INTRODUCTION

According to currently accepted theory, during the late stages of stellar evolution, stars develop instabilities in their outer layers, pulsate, and begin to eject copious quantities of material into space. This material enhances the density in the stellar outer atmosphere and circumstellar shell, with material entering from the bottom of the region and moving through the shell on a timescale of centuries to millennia, and eventually coming to pressure equilibrium with the interstellar medium. In regions in which the material in the shell has cooled sufficiently (T < 1500 K), part of the gas will condense into dust grains (Salpeter 1977). Le Sidaner & Le Bertre (1993) estimate the temperature of the hottest grains in two asymptotic giant branch (AGB) stars to be in the range of 750–950 K. The type of grain that is produced depends on the composition of the outflowing material. In oxygen-rich circumstellar shells, the oxygen remains after the formation of CO (the most stable molecule) will condense into oxygen-rich solids such as silicates (Nuth & Hecht 1990). On the other hand, in carbon-rich circumstellar shells, part of the remaining carbon will condense into SiC grains.

During 1983 IRAS (Neugebauer et al. 1984) obtained infrared broadband fluxes of point sources (PSC) at 12, 25, 60, and 100 μm. Simultaneously, the low-resolution spectrometer (LRS) obtained spectra in the 8–22 μm range of nearly all sources brighter than 2 Jy (Wildeman, Beirtma, & Wesselius 1983). The spectra were obtained in two overlapping spectral regions, from 8–13 μm and 11–22 μm. These spectra are ideally suited to study dust grain signatures, since the emission bands of silicate dust at 10 and 18 μm and of silicon carbide, SiC, at 11.2 μm are found in this wavelength region. IRAS observed sources during three to many scans, depending on the ecliptic longitude, simultaneously obtaining their LRS spectra. Averaged LRS spectra of the nearly 7000 brighter sources have been published so far (IRAS Science Team 1986; Volk & Cohen 1990; Volk et al. 1991), but this is a subset of the over 150,000 individual spectral scans of about 50,000 objects actually obtained.

The purpose of this paper is to demonstrate unambiguously, for the first time, that the 10 μm silicate feature originating in an optically thin shell of an evolved star varies with the optical light curve of a central star. We present the LRS data for AU Cygni in order to illustrate this point. Previously, ground-based observations of Miras in the 10 μm region have suggested that the dust emission appears to vary with time (Sutton, Storey, & Townes 1978; McCarthy, Howell, & Low 1978; Le Bertre 1993) primarily because the 10 μm region appears to show larger variations in flux than measurements taken on either side of the emission feature. However, the advent of the individual IRAS-LRS scans provide sufficiently homogeneous data using the same instrument, making it possible to study both the detailed shape and the strength of the silicate emission feature at different phases of the light cycle.

2. DATA AND ANALYSIS

The published LRS spectrum of AU Cygni (IRAS 20165+3413; R.A. = 20°16'35"5, decl. = +34°13'49" (1950); l = 75°9, b = -0°85; M6e, Mira, P = 435°) consists of the average of five spectral scans. These scans were extracted from the extended database (VMS/pont source version, originally obtained by request through Paul Wesselius at SRON, Groningen) and analyzed with the software that we developed at the Center for Astrophysics and Space Astronomy of the University of Colorado. The file associated with each spectral scan contains its time tag (expressed in terms of 0.1 s since 1981 January 1), preliminary broadband 12, 25, 60, and 100 μm fluxes, as well as other information. We obtained updated individual time-tagged point source fluxes (PSC) for our sources from IPAC (the Infrared Processing and Analysis Center).

Figure 1 shows five LRS spectral scans of AU Cyg. Three of the scans were taken at very similar phases (0.18, 0.18,
0.20, and two others were taken about 7.5 months later, both at phase 0.58. The long-wavelength spectrum of scan 2 is not usable because of onboard timing errors. Variations in flux by about a factor of 2 are clearly evident and are real rather than an artifact of the instrument, since the 12 μm broadband fluxes taken with a different instrument show a similar variation. As can be seen in Figure 1a, the flux level of scans taken at similar phases are very similar. Also, spectra of star that show only a photospheric continuum, such as the low-amplitude variable π Aur (M3.5 II, lc, Δm = 0.1 mag), are very similar at all times (Fig. 1b).

The observational data for AU Cyg are listed in Table 1. IPAC combines the data from second- and hour-confirmed sightings. Hence, only one set of PSC fluxes is given for phase 0.18 and 0.58, even though two LRS scans are available for each of these phases. There are slight differences in the value of the time tags obtained from the extended database and the values provided by IPAC depending on which of the second-, hour-, or orbit-confirmed sighting was referenced in the two databases.

The LRS spectral scans are incorrectly calibrated, espe-
TABLE 2

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$F_{\text{abs}}(10 \mu\text{m})$ (W m$^{-2}$ m$^{-1}$)</th>
<th>$F_{\text{cont}}(10 \mu\text{m})$ (W m$^{-2}$ m$^{-1}$)</th>
<th>$F(12 \mu\text{m})$ (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>$4.8 \times 10^{-12}$</td>
<td>$2.4 \times 10^{-12}$</td>
<td>103</td>
</tr>
<tr>
<td>0.58</td>
<td>$2.4 \times 10^{-12}$</td>
<td>$1.3 \times 10^{-12}$</td>
<td>58</td>
</tr>
<tr>
<td>Difference</td>
<td>0.75 mag</td>
<td>0.57 mag</td>
<td>0.63 mag</td>
</tr>
<tr>
<td>(max-min)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both the star and the dust contribute to the emission in the 10 $\mu$m region. We have chosen to represent the IR continuum spectral energy distribution of the star by a blackbody energy distribution. Large dust grains (>2 $\mu$m) also produce a smooth (featureless) continuum in this wavelength region, whereas small grains, in addition, have a very strong wavelength-dependent component to their emission (Sivagnanam, Le Squeren, & Foyle 1988; Dominik, Sedlmayr, & Gail 1993). The emissivity of the grains is parameterized by their $\epsilon_g(a)$ values, where $a$ is the size of the grain. At a first approximation, we combine the continuum contribution from the star and the dust and subtract it from the observed spectrum by fitting the (blackbody) continuum to the LRS outside of the observed emission feature, usually around 8 and 13 $\mu$m. This difference spectrum ($F_j - F_{\text{cont}}$) gives the shape of the emission feature and allows us to define the contrast parameter. The contrast is a measure of the amount of emission due to small silicate dust grains and is defined as ($F_j - F_{\text{cont}}$)/$F_{\text{cont}}$, where $F_j$ is the observed flux and $F_{\text{cont}}$ is the continuum (blackbody) flux underlying the emission feature; both quantities are evaluated at the wavelength of the 10 $\mu$m silicate peak (Tables 1 and 2). A contrast of zero indicates no silicate dust emission. The results of this fitting procedure in Figure 2 for LRS scans taken at phase $\Phi = 0.18$ and $\Phi = 0.58$. The observed spectral scans, the blackbody energy distribution of 510 and 480 K (top panels), and the difference spectra (observed LRS-continuum flux) (bottom panels) are plotted for these phases.

3. DISCUSSION

Figure 3 and the data in Table 1 show very clearly that the PSC fluxes and the contrast of the 10 $\mu$m silicate feature show similar behavior to the optical light curve, obtained from the AAVSO (American Association of Variable Star Observers). Both are strongest near optical maximum and smallest near optical minimum. The average contrast for AU Cyg varies from 1.17 near optical maximum ($\Phi = 0.18$) to 0.84 near optical minimum ($\Phi = 0.58$), while the PSC flux varies from 103 to 58 Jy (by 0.63 mag), respectively. The observed flux at the peak of the silicate emission feature varies by 0.75 mag (from $4.8 \times 10^{-12}$ to $2.4 \times 10^{-12}$ W m$^{-2}$ m$^{-1}$), whereas the flux of the underlying continuum at the wavelength of peak emission varies by 0.57 mag (from $2.2 \times 10^{-12}$ to $1.3 \times 10^{-12}$ W m$^{-2}$ m$^{-1}$, Table 2). Hence, the decrease in contrast is due to the greater decrease in band emission relative to that of the underlying continuum. The shape of the circumstellar 10 $\mu$m feature is narrower than the feature observed in the Trapezium. Larger dust grains (>0.75 $\mu$m in radius) and larger optical depths will tend to broaden the feature (Cohen & Witteborn 1985; Simpson 1991). Overlaying the difference spectra near maximum and minimum shows that the shapes of the 10 and 18 $\mu$m silicate emission features do not vary measurably with time; neither does the flux ratio of the two bands show variations with time.

The contrast is related to the optical depth of the circumstellar shell. The optical depth at 10 $\mu$m, $\tau_{10}$, depends on the total number of grains in our line of sight, the temperature distribution in the shell, and the emissivity of the grains. As $\tau_{10}$ increases, the contrast will increase from zero to a maximum value. As the shells become optically thick, the 10 $\mu$m emission feature broadens slightly, self-absorption occurs around 10 $\mu$m, and the emission feature of optically thin and moderately thick shells become the absorption feature seen from optically thick shells. Hence, the contrast as a function of $\tau_{10}$, after reaching a maximum value, will decrease, become again zero, and is negative for optically thick shells.

The optical depth of the AU Cyg shell does not appear to go into self-absorption since the shape of the emission near maximum and minimum are very similar; no broadening of the line is evident. Since the contrast decreases as the star becomes fainter, the simplest interpretation is that the total number of grains in our line of sight, hence $\tau_{10}$, decreases. However, during the pulsational cycle of Miras as the shock passes out through the atmosphere and into the circumstellar shell, we expect that periodic flux and temperature variations should produce alternate evaporations and condensations of dust near the inner dust-shell radius, as the dust condensation radius moves periodically inward and outward. Since the star is cooler near minimum (Strecker 1973; Hoffmeister, Richter, & Wenzel 1985), more dust should be in our line of sight at minimum and $\tau_{10}$, and the contrast should increase, opposite to what we observe.

We propose that the band emission from silicate grains and the continuum emission in this wavelength region is
controlled by grains of different sizes and that the size distribution of grains varies throughout the light cycle due to the evaporation and recondensation of grains. The band emission from silicates is most efficient from small grains (Draine & Anderson 1985), whereas larger grains (> 2 μm) produce primarily continuum emission. As the luminosity and temperature of the star vary, we propose that the relative number of small to large grains will vary. With increasing luminosity and temperature, the larger grains will tend to evaporate near the inner radius of the dust shell, leaving a population of small grains behind. Hence, near maximum we expect to observe proportionally more emission from small grains and a stronger emission feature relative to the continuum. This is observed for AU Cyg—the contrast increases between minimum and maximum light. We illustrate this concept with a simple cartoon. Let the star be represented by a variable light source and the dust grains by water droplets sprayed onto a sheet of glass. Smaller water droplets/dust-grains will exist closer to the light source/star because it is hotter there and larger droplets/grains will exist at larger distances from the light source. As the light/ star brightens and the source becomes hotter, the droplets/grains begin to evaporate leaving a larger percentage of smaller droplets/grains behind. As a result we find that the emission near maximum comes from grains that have a greater population of small grains relative to large grains. The existence of a population of very small grains has been postulated to be present in the interstellar medium in order to explain the excess 12 and 25 μm emission observed by IRAS (see Cox & Mezger 1989). We propose that a population of small grains is already present in circumstellar material.

Our conclusions derived from the data of AU Cyg are not unique. Using the same procedure, we find that the contrast is smaller near minimum for the Mira variables R Cet (M4e, \( P = 166^d \)) and R LMi (M6.5e, \( P = 372^d \)) (Little-Marenin & Stencel 1992) and seems to apply in general to Miras with optically thin shells. The PSC fluxes and contrasts of about 30 Miras with observed phases near optical maximum and minimum and well-determined periods appear to vary in phase with their optical light curves (Little-Marenin, Staley, & Stencel 1993). The fluxes and contrasts are largest near maximum and smallest near minimum. The 12 μm variation of about 0.6 mag for AU Cyg is within the range of 0.4–2.0 mag we estimate for 30 Miras and is consistent with the magnitude ranges observed by Le Bertre (1993) and Africano et al. (1992). Similarly, McCarthy et al. (1978) and Le Sidaner & Le Bertre (1993) observed variations in the bolometric and 10.2 μm flux by a factor of 2.5 (1 mag). In general, the amplitude of variation for Miras with optically thin shells decreases with wavelength from an average of 1 mag at 1 μm to about 0.7 mag around 20 μm (a minimum of 0.5 mag occurs around 4 μm). However, the amplitudes around 10 μm, where silicate emits most strongly, are typically around 1 mag, larger than either at 8.4 or 12.7 μm, and Le Bertre (1993) suggests that the variation of the dust emission is larger than that of the underlying continuum, i.e., that the contrast varies with time, similar to what we have found. We find a greater degree of time variability in the LRS than Hron & Aringer (1994), who appear to have used a less than optimum selection of stars for their study.

The formation of new dust near minimum is borne out by direct interferometric measurements (Bester et al. 1991; Danchi et al. 1994). These authors find that the silicate dust extends to within about 3 \( R_\ast \), where the temperature is around 800–1300 K and new dust appears to form at even smaller radii during minimum luminosity in most long-period variables (LPV), but may form at all phases in others, but very few observations are as yet available (Danichi et al. 1994). Since interferometric observations suggest that the amount of dust in our line of sight increases near minimum, whereas our and Le Bertre's data indicate that the contrast of the silicate emission decreases near this phase, Le Bertre (1993) suggests that the decrease in contrast is due to a change in the nature of the silicate grains themselves, which affects the emissivity of the grains. The silicate emission samples the inner, hotter parts of a circumstellar shell where evaporation and condensation of grains are most pronounced. Therefore, Le Bertre suggests that the grains themselves, likely to be “dirty” silicates, change during the pulsational cycle as the mantles of the grains evaporate and recondense. We propose instead that circumstellar dust has a significant population of small grains, which gets enhanced near maximum due to evaporation of larger grains.

Theoretical calculation of the formation of “dirty” dust grains in the winds of M stars by Dominik et al. (1993) show that below about 600 K dust formation is complete. But they find that the number of dust grains present between 1500 K (where dust formation starts) and about 600 K (where dust formation is complete) is a very strong function of temperature, and that the size distribution of “clean” and “dirty” grains that form are significantly different. Many more small “clean” grains form than “dirty” grains. It is possible that “dirty” grains are more easily evaporated, leaving behind a larger percentage of smaller “clean” grains that produce the observed enhancement of the 10 μm emission feature. In order to put the above arguments onto solid footing, we will need to model the transfer of radiation through the shell accurately, taking changes in the emissivities and the size distribution of emitting grains into account.

4. CONCLUSIONS

Analysis of multiple low-resolution scans of the Mira variable AU Cyg show for the first time very clearly that the contrast and the 12 μm point source flux of the 10 μm emission feature show variability during the optical light cycle of the star. The flux and contrast are strongest near optical maximum and weakest near minimum. Since more dust is likely to form during minimum, as the condensation radius moves inward while the star cools, one would expect the contrast to be larger at minimum, contrary to what is observed. We suggest that the size distribution of the grains changes significantly between maximum and minimum light, and we postulate the presence of a significant population of small dust grains, which is enhanced near maximum due to the evaporation of larger grains. There is no indication that the optical depth of the shell changed drastically between the two phases. The similarity in shape of the emission feature near maximum and minimum precludes a significant amount of self-absorption occurring near minimum.

In order to understand the observed data, we will need to run radiative transfer models at both phases. These models will need to incorporate changes in the emissivities of the dust grains and differences in size distributions as a function of phase in order to be able to model both phases. Due to
the nature of the IRAS spacecraft, we are usually able to obtain spectra at only two distinct phases. In order to understand the apparently complex processes occurring during dust formation and destruction, a sampling of spectra during a complete light cycle will be needed.

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REFERENCES


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