EXTENDED 60 µm EMISSION FROM NEARBY MIRA VARIABLES

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ABSTRACT

The IRAS satellite has detected extended emission around a number of evolved stars. Individual IRAS scans of nearby Mira variables which showed emission from circumstellar dust and for which distance estimates were available were examined. Extended emission at 60 µm was detected for R Cas, o Cet, R Leo, U Ori, and possibly for R Hor. The Leung code for the calculation of radiative transfer in a circumstellar dust shell was used to calculate the emission from model dust shells composed of silicate grains. The output was convolved with the IRAS beam profile to determine whether steady mass loss could explain the observed extension. The observed extensions for o Cet, R Hor and U Ori could be due to steady mass loss, while the model calculations do not produce enough extension to explain the observations of R Cas and R Leo.

1. INTRODUCTION

IRAS (the Infrared Astronomical Satellite; Neugebauer et al. 1984) has detected extended 60 and 100 µm emission at an arcmin scale around a number of evolved stars (Stencel et al. 1989; Hawkins 1989, 1990; Young et al. 1993a,b). Individual scans of some objects were seen to be broader than those of point sources. This extended emission is believed to come from dust in extensive envelopes formed around these stars as a result of mass loss from the central star. It is hoped that the information on the shell extension contained in the IRAS data can be used to derive information on the spatial structure of the shells.

The extension is generally not apparent at 12 and 25 µm because the warm dust radiating at these wavelengths is relatively close to the star. At 100 µm, the prevalent infrared cirrus generally renders the background too nonuniform for the detection of faint extended emission. We have thus concentrated our work on the 60 µm bandpass.

Young et al. (1993a,b) surveyed a sample of 512 stars for extended emission, and fit the observations with fairly simple dust shell models (e.g., deriving only an average dust temperature). In a different approach, we selected a smaller sample of stars known to show dust emission and possibly for R Hor. The Leung code for the calculation of radiative transfer in a circumstellar dust shell was used to calculate the emission from model dust shells composed of silicate grains. The output was convolved with the IRAS beam profile to determine whether steady mass loss could explain the observed extension. The observed extensions for o Cet, R Hor and U Ori could be due to steady mass loss, while the model calculations do not produce enough extension to explain the observations of R Cas and R Leo.

2. THE SAMPLE

Wyatt & Cahn (1983) present a sample of 124 Mira variables in the solar neighborhood for which they estimate distances. For those stars closer than about 700 pc, these distances agree to within about 20% of those calculated using the Celis (1980, 1981) relation between mean absolute visual magnitude at maximum light, period, and spectral class at maximum light (Bowers & Hagen 1984). From Wyatt and Cahn’s list we selected those with IRAS Low Resolution Spectrometer (LRS) classes given in the point source catalog as 2n or 6n, indicating silicate emission. No LRS class is given for R Leo and o Cet in the IRAS point source catalog. However, these objects were known previously to us to have infrared emission greater than that expected from a photosphere alone and therefore they were included. LRS observations of these two objects were obtained from the LRS extended database maintained at the University of Colorado. The LRS observations for all stars for which dust shell models were constructed were corrected according to the recalibration of Cohen et al. (1992).

The 34 Miras from the sample which are known to show dust emission are plotted in the infrared two-color diagram of Van der Veen & Habing (1988) in Fig. 1. Note that nearly all are found in region II, which they claim is mainly inhabited by objects with thin oxygen-rich dust shells, consistent with our selection of optically visible Mira variables with
silicate emission. The objects which do not fall within or near region II are now discussed individually.

R Aql is the single object in section VIIb. Its [25]–[60] color is very red in comparison to its [12]–[25] color. Examination of the individual scans at 60 and 100 μm and the 60 μm map showed that R Aql is sitting near a large extended source of emission and that the 60 μm observations are not simply due to the star and any circumstellar shell resulting from its own mass loss.

Z Sgr is the object near the center of region VII. It also has a very red [25]–[60] color. The individual 60 μm scans show a very bumpy background, and thus the red color could be due to the star’s environment and not due to its own mass loss.

R Cet and Z Cyg are the two rightmost sources in region IIIa. Both have strong silicate emission features (LRS classes 29 and 69, respectively), but have relatively blue [25]–[60] colors. Note that R Cet and Z Cyg are the only Miras in the samples with periods less than 300 days.

We have looked at the position of the stars plotted in the two-color diagram in Fig. 1 as a function of period, spectral type at maximum, and LRS class. As stated above, the two short-period Miras are seen at the right-hand edge of the sample. However, once the period is greater than 300 days, there seems to be no correlation with infrared colors. Furthermore, there appears to be no correlation between spectral type at maximum and the star’s position within the diagram.

The stars in Fig. 1 have been plotted with symbols indicative of their LRS classes. Generally, stars with strong silicate features tend to appear farther to the right in the diagram. As seen in Sec. 4.1.B, increasing τ (which increases the contrast in the silicate feature for optically thin shells) reddens the [12]–[25] color. Thus, as n increases for LRS class 2n sources, one would expect a redder [12]–[25] color. However, stars with very different silicate emission features can show very similar infrared colors. Note particularly the three objects near [12]–[25] = −0.75 and [25]–[60] = −1.9. Nearly identical infrared colors are seen for Z Pup (LRS class 29), W Cnc (23), and R Tau (21). Shell models based only on point source fluxes, without considering the strength of the silicate feature, will be inadequate for modelling individual objects! This point has been made previously by David & Papoular (1990).

3. OBSERVED EXTENSIONS

We are seeking extension due to optically thin dust surrounding a bright central source. The star at the center will dominate the observed emission, and any extension in the dust shell will appear as a broadening of the scan profile at low intensity level. Examination of the noise level and the smoothness of the background of the individual 60 μm IRAS scans shows that peak fluxes greater than roughly 20 Jy are normally needed in order for the faint extension to have sufficient signal-to-noise ratio for modelling purposes. However, we did not adopt an absolute 20 Jy peak flux cutoff, but rather selected stars from the sample based on the signal-to-noise seen in examining the individual scans.

In the survey mode, the scan rate of the satellite was 3.85 arcmin per s, with a sampling rate for 60 μm observations of 8 Hz. Thus the detector output was sampled only every 0.48 arcmin. IPAC software provides spline fits to the observations, making the scans appear more highly sampled. Coaddition of scans sampled at different points can help to increase the effective sampling rate. However, the coaddition of the scans can artificially broaden the summed scans. This can happen if one or more of the scans is significantly broader than the others, or if the same are not well centered. Therefore, we chose to use the individual scans of our sources rather than coadditions.

A useful indicator of scan extension is the full width of a scan at 10% of peak intensity, or W(10%). This quantity is routinely provided by IPAC software, both for individual scans and for coadditions. We will use this to quantify the detection and modelling of extension. We believe that it is a reasonable indicator of shell extension for the stars we considered in this project, in which dust forms close to the central star and probably falls off as the square of the radius. Figure 2 shows the convolution of the flux from a model dust shell representative of those considered in this project with the IRAS beam profile. Although the extension is most noticeable at low intensity level, the scan profile is broadened at all intensity levels. The increase in W(10%) is clearly seen. Sources included in this project showed this type of scan profile, with the central peak smoothly blending with extended wings. None showed the distinct “shoulders” in the low-level extended emission seen in Y CVn (see Fig. 1 in Young et al. 1993a).

Very bright point sources can appear extended compared to fainter sources. Some sources in Stencel et al. (1989) and in this project as well, actually show lower extension than the comparison profile. The comparison profile used in our modelling was generated from scans of the asteroid Ceres and the stars β Gru, g Her, and α Boo, objects not expected to be extended. The W(10%) of this profile is 2.53 arcmin, which is more extended than the IRAS point source template, which has a W(10%) of approximately 2.45 arcmin (Beich-
which is significantly brighter (300 Jy) at 60 μm than are g Her (24 Jy) and β Gru (41 Jy). The average W(10%) for β Gru is only 2.45 arcmin. Note that some of the W(10%) of the fainter sources given in Table 1 are less than that of the comparison profile; thus our comparison profile probably predicts too great an extension for the fainter objects.

Maps were made at the Infrared Processing and Analysis Center (IPAC) for sources with scans with sufficiently high signal-to-noise ratios for the detection of faint extension. Sources such as R Aql which were sitting within additional sources of extended emission were eliminated.

Only scans in which the detector center passed within 1.7 arcmin of the central star were considered; this typically included 6 to 12 scans per star. For a number of our extended sources, the dust shell was in fact detected in scans in which the central star itself did not pass over the detector. However, a number of effects further discussed in Sec. 4.2 make these scans less straightforward to interpret, and they are not considered in this paper.

Only ten of the Miras we considered were isolated and had sufficient signal-to-noise. These sources are listed in Table 1. The average W(10%) of the individual scans, along with the standard deviation for a single observation, is given for each source. Examination of Table 1 shows that the sources R Cas, o Cet, R Hor, R Leo, and U Ori appear to be extended. All ten Miras in Table 1 were included in the survey of Young et al. (1993a), and there is good agreement regarding the detection or nondetection of source extension, with the exception of R Hor, which was not seen as extended by Young et al. R Hor has the smallest of the detected extensions. It should be noted that any extension detected at this level is marginal. Just as one or more especially broad scans could artificially increase the width of a coadded scan, so could they increase the average scan width. In this context it should be noted that 10 of the 13 scans of R Hor have W(10%) between 2.51 and 2.59 arcmin, while the other three are 2.68, 2.70, and 2.79 arcmin. If the three highest are omitted, the average drops to 2.56 arcmin. This is still somewhat extended when compared to the 2.45 arcmin W(10%) for the comparably bright β Gru; however, not significantly in light of the 0.5 arcmin 60 μm diffraction limit of the IRAS telescope.

4. MODELING

The emission from circumstellar dust was modelled using the Leung radiative transfer code CSDUST3 (Egan et al. 1988). The code uses a quasidiffusion method to solve the equation of transfer in a circumstellar dust cloud. The cloud is heated from the inside by a central star with a blackbody radiation field. The code output includes the observed flux as a function of wavelength (which can be compared to the IRAS LRS spectrum and point source fluxes) and of position (which can be convolved with the IRAS beam profile in order to predict extension).

Any acceptable model for a given source must reproduce the observed strength of the 10 μm silicate feature. In this work, the strength of the emission feature is determined by the ratio of the flux at 8 μm (where the dust contribution to the observed flux is minimal) to the flux at the peak of the emission feature. Although 8 μm is not an ideal wavelength for assessing the photospheric flux due to the presence of an SiO feature, we are restricted to wavelengths included in the LRS data.

The fluxes quoted in the IRAS point source catalog represent a convolution of the source emission with the wavelength response of the detectors. Thus, in order to properly predict the point source fluxes which would be observed from a model dust shell, the emergent flux calculated for a given model was convolved with the detector responses given in the IRAS Explanatory Supplement (Beichman et al. 1988).

We will consider models with a steady mass loss rate, which gives rise to dust density proportional to the inverse square of the radius. As the stellar surface temperature is too high to permit dust condensation at the photosphere, we will consider models with different inner shell radii, rmin (radii in units of the stellar radius will be denoted by a lower case r, and radii in cm will be denoted by an upper case R). All dust shell models were carried out to an outer radius Rmax of...
50,000 $R_\odot$ as the contribution to the total flux from dust beyond this is negligible.

For a 500 $R_\odot$ star, 50,000 $R_\odot$ corresponds to a distance of $1.74 \times 10^{15}$ cm, more than half a parsec. For a stellar angular diameter of 0.05", this shell would extend 20 arcmin from the central star. For the dust shell to be this extensive, mass loss at a velocity of 10 km s$^{-1}$ would have to have continued for 55,000 yr. Note also that the light travel time from the star to the outer shell radius is nearly two years, twice the period of a typical Mira variable. All along the line of sight in the outer parts of the dust shell the emission we see will arise from a combination of light travel times (from star to dust) and lookback times (from dust emission to us). Thus the dust emission in the outer regions will reflect some average of the stellar parameters (e.g., temperature, luminosity) over the stellar cycle.

Parameters which were varied in the modelling are $\tau$ (optical depth at 10 $\mu$m), $T_\star$ (effective temperature of the central star), and $r_{\text{inn}}$. All models discussed here were run for a star of radius 500 $R_\odot$. The infrared fluxes scale directly with $R_\star^2$, and as we match only relative, not absolute fluxes, running models for other values of stellar radii was not necessary.

### 4.1 Effect of Input Parameters on the 10 $\mu$m Silicate Emission Feature and Point Source Fluxes

#### 4.1.1 Optical constants

Unfortunately, absorption efficiencies for the dust around late-type stars are not well determined, and may in fact vary from star to star (Little-Marenin & Little 1990, Bedijn 1987). We have used the optical constants of Draine's (1985) astronomical silicate, for a grain radius of 0.1 $\mu$m. Unfortunately, these optical constants still do not provide a completely satisfactory fit to the observations, as they do not properly reproduce the detailed shape of the 10 $\mu$m emission feature. Therefore, the results given in this paper should be considered preliminary. However, matching the strength of the 10 $\mu$m feature in order to estimate $\tau$ should provide an accurate enough estimate of the quantity of dust to assess the feasibility of using models with steady mass loss to explain the observed extensions.

#### 4.1.2 Optical depth

As expected, increasing $\tau$ increases the strength of the 10 $\mu$m silicate feature (until $\tau$ approaches 1). The $\times$'s in Fig. 3 show the effect of increasing $\tau$ from $10^{-4}$ to 5. As $\tau$ increases, the [12]–[25] color gets redder. For thin shells ($\tau < 0.5$), the [25]–[60] color gets bluer as $\tau$ increases. Because the absorption efficiency at 25 $\mu$m is about a factor of 6 greater than that at 60 $\mu$m, the 25 $\mu$m flux increases faster than that at 60 $\mu$m. As the quantity of dust increases, moderate optical depth builds up more quickly at 25 $\mu$m than at 60 $\mu$m, slowing down the increase in flux at 25 $\mu$m, and causing the [25]–[60] color to redden as $\tau$ increases beyond 0.5. For the series of models discussed in Secs. 4.1.C and 4.1.D, $\tau$ values were adjusted to hold the height of the silicate emission feature constant.

#### 4.1.3 Inner shell radius

For constant stellar temperature, increasing $r_{\text{inn}}$ leads to cooler dust, more long-wavelength radiation, and redder infrared colors. The open circles in Fig. 3 represent a series of models in which the inner shell radius was varied from (2–20) $R_\ast$. The dust temperature at the inner shell radius (which we will call $T_{\text{inn}}$), ranges from 1400 K down to 360 K for the series of models plotted here. Estimates for the temperature at which silicates are expected to condense are above 1000 K (Gilman 1969). The models with larger $r_{\text{inn}}$ have $T_{\text{inn}}$ significantly less than this. If the mass loss is steady, $T_{\text{inn}}$ should reflect the condensation temperature of the dust. A low $T_{\text{inn}}$ might reflect that dust formation has ceased, and as the dust has moved outwards from the star, it has cooled.

#### 4.1.4 Stellar temperature

For constant inner shell radius, a cooler star has cooler dust and therefore redder infrared colors. The filled circles in Fig. 3 show the effect of decreasing stellar temperature from 3250 to 2000 K for $r_{\text{inn}}=10 R_\ast$. Both increasing $r_{\text{inn}}$ for constant $T_\star$, and decreasing $T_\star$ for constant $r_{\text{inn}}$ have the effect of decreasing the temperature of the dust at the inner shell radius. For the series of models plotted here, $T_{\text{inn}}$ ranges from 830 to 400 K.

Probaby a more realistic scenario is that dust would condense at the same temperature around all stars, such that $r_{\text{inn}}$ would be greater for hotter stars. A series of models was run by changing $r_{\text{inn}}$ as $T_\star$ varied in such a way that $T_{\text{inn}}$ remained nearly constant at about 1000 K. However, in this case, very little change is seen in the model's position in the two-color diagram; the [12]–[25] color only increased by...
0.11 and the [25]–[60] color by 0.05 as $T_*$ decreased from 3250 to 2000 K.

4.2 Effect of Input Parameters on Extension

The Leung code calculates the emergent intensity as a function of position on the surface of the dust cloud. We then convolved this output with the IRAS beam profile as the beam was stepped across the model dust shell. The IRAS beam profile in the in-scan direction was derived from the observed comparison scan profile described above. The cross-scan beam profile was determined for each detector from detector maps determined at IPAC by Moshir (1988). For scans in which the star crossed near the center of the detector, the modeling showed negligible dependence of the observed scan profile on the individual detector. For many of our extended sources, the dust shell was in fact detected by scans in which the detector did not pass over the central star. However, modeling these scans showed considerable dependence of the observed scan profile on the individual detector. Off-center scans of the brighter sources also show evidence of optical cross-talk. For these reasons, consideration of off-center scans will be left to future work.

For the convolution of the dust code output with the IRAS beam profile, the beam was divided into “pixels” of 0.1 arcmin on a side. The beam was then stepped over the predicted flux distribution in 0.1 arcmin steps. One of these 0.1 arcmin pixels contains the star and the inner regions of the dust shell; it will be referred to as the “central pixel.” The observed extension is thus dependent on the brightness of the outer regions of the shell relative to the sum of the brightness of the star and the inner regions of the dust shell. Since the model dust shells are spherically symmetric, the predicted specific intensity is azimuthally symmetric around the central star and is calculated as a function of “impact parameter” from the central star. The shell contribution to the central pixel was calculated by including dust emission included in a circle around the central star which has the same area as the square central pixel. For a star of angular diameter 0.05”, this central pixel would be 240 on a side, and the dust emission out to an “impact parameter” of 135 $R_*$ is included in the central pixel.

4.2.1 Stellar angular diameter

For a given combination of star and dust shell, increasing stellar angular diameter by moving the star closer to the Earth increases the observed extension, because the emission arising from a given radius in $R_*$ will be seen at a greater angular separation from the central star. The degree to which this occurs is seen for a number of models in Figs. 4–6, in which model fits to individual sources (discussed in Sec. 5) are plotted.

4.2.2 Optical depth

As dust optical depth increases, the ratio of the flux in the outer parts of the shell to that from the star plus inner shell increases, increasing the observed extension. The series of models depicted as X’s in Fig. 3 were convolved with the

Fig. 4. Comparison of predicted to observed extension for α Cet. The large filled circle represents the observed extension and adopted angular diameter for Mira. The small filled circles connected with dotted lines plot the predicted extension as a function of stellar angular diameter from a $T_*$=3250 K dust shell model (with other parameters listed in Table 2). The small open circles connected with a solid line are for $T_*$=2500 K. Other parameters are listed in Table 2.

IRAS beam assuming a star of angular diameter 0.05". $W(10\%)$ increased from 2.53 for $r=10^{-4}$ to 2.93 for $r=5$.

4.2.3 Inner shell radius

Increasing $r_{\text{min}}$ places more dust farther from the star, and increases extension. For the series of models discussed in Sec. 4.1.C (and plotted as open circles in Fig. 3), $W(10\%)$ increased from 2.69 to 2.96 as $r_{\text{min}}$ increased from 2 to 20 $R_*$, for stellar angular diameter of 0.05".

4.2.4 Stellar temperature

While both increasing $r_{\text{min}}$ for constant $T_*$ and decreasing $T_*$ for constant $r_{\text{min}}$ increase the long-wavelength flux in a similar manner, the effect on the extension is quite different. Little change in $W(10\%)$ is seen among the series of models with constant $r_{\text{min}}$ which were plotted as filled circles in Fig. 3. For a stellar angular diameter of 0.05", $W(10\%)$ increased from 2.78 to 2.88 as $T_*$ was increased from 2000 to 3250 K.

Fig. 5. Comparison of predicted to observed extension for U Ori. The large filled circle represents the observed extension and adopted angular diameter for U Ori. Other symbols are as in Fig. 4.
Although changing $T_\ast$ while varying $r_{\text{min}}$ to keep $T_{\text{inn}}$ constant scarcely affects the long-wavelength fluxes, it does significantly affect the extension. For the series of models discussed in Sec. 4.1.4 (but not plotted in Fig. 3), $r_{\text{min}}$ was adjusted so that $T_{\text{inn}}$ was held nearly constant at about 1000 K. For a stellar angular diameter of 0.05", $W(10\%)$ increased from 2.68 to 2.83 as $T_\ast$ was increased from 2000 to 3250 K. The reason for the increased extension at higher stellar temperature is that in order to keep $T_{\text{inn}}$ constant, $r_{\text{min}}$ must increase, and the dust is farther from the star.

5. RESULTS AND DISCUSSION

For models run to compare to individual sources, $r$ was adjusted until the strength of the 10 $\mu$m emission feature matched the LRS observations. For stellar temperatures of 3250 and 2500 K, $r_{\text{min}}$ was adjusted until a satisfactory fit was found to the point source fluxes. In general, the flux at 12 and 60 $\mu$m was well matched, but the 25 and 100 $\mu$m fluxes could not always be reproduced. Model parameters which adequately matched the LRS and point source observations for the extended sources are listed in Table 2. Neither of the pairs of model fits in Table 2 matches the observations significantly better than the other. In fact, the stars' temperatures are expected to vary over approximately this range during their pulsational cycles. The adopted stellar angular diameter is also given in Table 2. The angular diameters of Mira and R Leo have been measured by speckle interferometry at many wavelengths (Bonneau et al. 1982; Labeyrie et al. 1977). The angular diameter is strongly wavelength-dependent and increases greatly at the wavelengths of TiO lines. Bonneau et al. estimated the angular diameter of Mira in the continuum to be 28±6 mas. The measurements of R Leo were not made in the wavelengths at which Mira showed the smallest angular diameter. Thus for stars other than Mira, we have scaled Mira's angular diameter by the relative distances of the stars as given by Wyatt & Cahn (1983). Errors in angular diameters for the other stars were estimated by doubling the percent error for Mira in an attempt to include the errors in distance and in the assumption that all the Miras have the same linear diameter.

The variation of the predicted extensions with angular diameter from the two models listed for each source in Table 2 is plotted in Figs. 4–6 against stellar angular diameter, along with a point representing the observed extension and the adopted stellar angular diameter. For U Ori, R Hor, and Mira, steady mass loss appears capable of explaining the observed extension. R Cas appears somewhat more extended than the models predict.

The strength of the emission feature in R Leo is much too low to be produced by the quantity of silicate dust that would be needed to explain the observed extension. It is probable that silicates are not responsible for the infrared excess of R Leo; Little-Marenin & Little (1990) classify R Leo as showing a weak broad feature from 9–15 $\mu$m, possibly due to aluminum oxide.

One way in which extension could be increased that has not yet been discussed here is if the dust density fell off less rapidly than as the inverse square of the radius. However, this is unlikely to explain the extension of R Cas and R Leo. If the dust density falls off more slowly, the infrared colors become much redder, and do not fit the point source fluxes.

Nine of the ten sources in Table 2 were located in region II of the color–color diagram (the tenth, R Leo, lies in region I due to the weakness of its dust emission). They were scattered randomly throughout region II. There was no correlation between an object's position within region II and the detection or nondetection of extension. However, the five sources in Table 2 which did not show extension, RR Aql, U Her, RU Her, S Pic, and R Ser, are all more distant than the extended sources. The smaller angular diameter of the central star likely explains the lack of extension. Thus, for the sample of stars included here, physical proximity is more important than any particular property of the dust shell in the detection of extension.

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