LARGE CIRCUMBINARY DUST GRAINS AROUND EVOLVED GIANTS?

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ABSTRACT

We have detected continuum emission at 450 \( \mu \text{m} \), 850 \( \mu \text{m} \), and 1.35 mm from SS Lep (or 17 Lep), 3 Pup, and probably BM Gem, respectively, which are likely or confirmed binary systems consisting of at least one evolved giant. The observed submillimeter fluxes are probably emitted by grains rather than ionized gas. The fluxes are larger than those expected from a “normal” dusty wind; the dust temperature is \( \lesssim 70 \text{ K} \) within 6\( ^\circ \) of the stars. To explain why grains are so cold near the star, we suggest that the emission at \( \lambda \geq 450 \mu\text{m} \) is produced by particles as large as 0.1 mm in radius and that these large particles probably have grown by coagulation in circumbinary orbiting disks with masses \( \geq 5 \times 10^{-5} \text{g} \).

Subject headings: circumstellar matter — stars: mass loss — stars: winds, outflows

1. INTRODUCTION

The growth of solids into planetesimals in circumstellar disks is a major unsolved astrophysical problem. Almost all investigations of dust disks have concentrated on pre-main-sequence stars, but there are some post-main-sequence binary stars that possess orbiting circumstellar dust disks. We are studying disks in evolved systems with the goal of learning more about particle growth.

Accretion disks around a mass-receiving star in mass-exchange binary systems such as cataclysmic variables and symbiotic stars have been studied for many years. In an accretion disk, the lifetime of an individual grain may be short even if the system is long-lived. In contrast, in a circumbinary disk, the particles orbit both stars and are not being continuously destroyed. As a result, in circumbinary disks, particles may survive enough orbits to grow by coagulation to sizes as large as 1 mm. With only a few known examples of this phenomenon, such as the Red Rectangle and AC Her (Waters et al. 1993; Jura & Kahane 1999; Jura, Chen, & Werner 2000; Molster et al. 2001), we hope to identify more such systems.

Because small spherical grains do not emit efficiently at wavelengths much larger than their size (see, e.g., Spitzer 1978), one way to identify “big” particles is to observe at relatively low frequencies. Therefore, we have obtained millimeter and submillimeter observations of SS Lep (\( m_v = 5.0 \) mag, \( \text{period} = 260 \) days, \( A1 + M4; \) Cowley 1967; Welty & Wade 1995) and 3 Pup (\( m_v = 4.0 \) mag, \( \text{period} = 161 \) days, \( A2 + ?; \) Plets, Waelkens, & Trams 1995) because they are A-type stars in the Yale Bright Star Catalog with anomalously high \( I R A S \) fluxes (Jura & Kleinmann 1990), and we suspected that they may have circumstellar disks. As part of this program, we also obtained data for BM Gem, a highly luminous carbon star with oxygen-rich circumstellar matter that may also possess a long-lived orbiting disk (Kahane et al. 1998).

There are many previous infrared studies of evolved binary stars (see, e.g., Friedemann, Gurttler, & Lowe 1996). A system that might have some properties in common with SS Lep and 3 Pup is the binary containing the post–main-sequence luminous A-type star \( \epsilon \) Aur (\( M_\star \leq -6.0 \) mag), which has a companion of unknown type that is surrounded by a dust disk containing grains larger than 5 \( \mu \text{m} \) (Lissauer et al. 1996). Here we consider circumbinary environments where the grains may be more than an order of magnitude larger in size and thus \( 10^5 \) times more massive than those found around the companion to \( \epsilon \) Aur.

In contrast to their infrared properties, little is known about submillimeter dust emission from evolved binary stars. Symbiotic stars have been detected at \( \lambda > 100 \mu\text{m} \) (Seaquist & Taylor 1992; Ivison et al. 1995; Corradi et al. 1999), but this emission is probably produced by ionized gas and not dust. In the systems discussed here, thermal emission by dust probably dominates at \( \lambda \lesssim 1350 \mu\text{m} \).

2. OBSERVATIONS

The 1.35 mm flux measurements were obtained on 1999 January 21 in the service observing mode with the Submillimeter Common-User Bolometer Array (SCUBA) camera (Holland et al. 1999) using the photometric mode on the James Clerk Maxwell Telescope (JCMT) at Mauna Kea, Hawaii. The telescope half-power beam diameter at 1.35 mm was 19\( ^\circ \). The atmospheric opacity was scaled from simultaneous measurements from the Caltech Submillimeter Observatory radiometer and ranged between 0.11 and 0.13. The data were reduced and calibrated using the “SCUBA User Reduction Facility” (SURF; Jenness 1998). The secondary calibrator, RAFlG 618, was used to calibrate fluxes with an assumed flux of 2.49 Jy. Integration times of 30 and 36 minutes yielded the measured fluxes reported in Table 1.

The 450 and 850 \( \mu\text{m} \) fluxes were measured on 2000 January 31, again at the JCMT in the service observing mode with the SCUBA camera in the photometric mode following procedures similar to those for our previous observations. The secondary calibrators were RAFlG 618 and OH 231.8+4.2 with assumed fluxes of 4.57 and 11.9 Jy at 850 \( \mu\text{m} \), respectively, and 2.52 and 10.5 Jy at 450 \( \mu\text{m} \), respectively. The half-power beam diameters were 8\( ^\circ \) and 12\( ^\circ \) at 450 and 850 \( \mu\text{m} \), respectively. The results are reported in Table 1.

The listed uncertainties represent the rms noise levels and do not include an estimated 10% calibration error at 1.35 mm and 850 \( \mu\text{m} \) and a 20% calibration error at 450 \( \mu\text{m} \). With an extragalactic background at 850 \( \mu\text{m} \) of probably...
TABLE 1

| Property                      | SS Lep | 3 Pup | BM Gem |
|-------------------------------|--------|-------|--------|
| \(D, \, (\text{kpc})\)       | 0.33\(^a\) | 2.1\(^b\) | 1.5\(^a\) |
| \(T, \, (K)\) (component A) | 9000\(^c\) | 9000 | 3000 |
| \(T, \, (K)\) (component B) | 3500\(^a\) | ? | ? |
| \(R, \, (\times 10^{12} \, \text{cm})\) (component A) | 1.1 | 9.5 | 30 |
| \(R, \, (\times 10^{12} \, \text{cm})\) (component B) | 7.4 | ? | ? |
| \(L, \, (\times 10^3 L_\odot)\) (component A) | 1.5 | 110 | 13 |
| \(L, \, (\times 10^3 L_\odot)\) (component B) | 1.5 | ? | ? |
| \(F_{\text{p}}(100 \, \mu\text{m})\) (Jy) | 3.8 | 7.3 | 1.3 |
| \(F_{\text{p}}(450 \, \mu\text{m})\) (mJy) | 148 (23) | 189 (48) | 24 (13) |
| \(F_{\text{p}}(850 \, \mu\text{m})\) (mJy) | 58.6 (2.1) | 81.4 (3.3) | 6.6 (1.9) |
| \(F_{\text{p}}(1350 \, \mu\text{m})\) (mJy) | 25.4 (2.4) | 46.2 (3.3) | 5 (2) |
| \(T_{\text{pred}}(K), \, p = 1\) | 123 | \(\geq 130\) | \(\geq 79\) |
| \(T_{\text{pred}}(K), \, p = 0\) | \(\leq 38\) | \(\leq 44\) | \(\leq 57\) |
| \(T_{\text{pred}}(K), \, p = 0\) | \(\leq 600\) | \(\geq \infty\) | \(\geq \infty\) |
| \(M_{\text{det}} \, (\times 10^3 \, \text{g})\) | 5 | 300 | 10 |
| \(R_{\text{det}} \, (\times 10^2 \, \text{cm})\) | 5.6 | 28 | 2.0 |
| \(M_{\text{det}} \, (M_\odot)\) | 2.3 | 77 | 0.01 |
| \(M_{\text{det}} \, (\times 10^3 \, \text{g} \, \text{s}^{-1})\) | 5 | 75 | 15 |
| \(t_{\text{rad}} \, (1000 \, \text{yr})\) | \(\geq 3\) | \(\geq 13\) | \(\geq 22\) |

\(^a\) From Hipparcos.
\(^b\) From Plets et al. 1995.
\(^c\) From Kahane et al. 1998.
\(^d\) From Blondel et al. 1993.
\(^e\) Extrapolated from Dyck, Van Belle, & Thompson 1998.
\(^f\) Calculation based on parameter values in Table 1.

fewer than five sources per degree squared brighter than 50 mJy (Smail, Ivison, & Blain 1997), it is unlikely that source confusion contaminates our observations.

3. STELLAR PARAMETERS

For many years, it was thought that the A-type star in SS Lep lies on the main sequence; it has a luminosity class V in the Yale Bright Star Catalog. However, the distance measured with the Hipparcos satellite is 330 pc. With \(A_v \sim 0.4\) mag (see Blondel, Talavera, & Djie 1993) and \(m_v = 5.0\) mag, then \(M_v = -3.0\) mag, and thus this A-type star lies well above the main sequence (see Perryman et al. 1995). Analysis of the Doppler motions show that the A-type star has 3.5 times the mass of the M-type companion (Welty & Wade 1995), and it is unlikely that both stars are in pre-main-sequence evolution since the timescales for remaining above the main sequence are such a strong function of stellar mass (Palla & Stahler 1993). Instead, it appears that this is an interacting binary in which both stars have evolved beyond the main sequence (Pols et al. 1991). The binary companion to 3 Pup is unseen (Plets et al. 1995), while it is only suspected that BM Gem possesses a companion (Kahane et al. 1998). Our estimates for the distance \(D\), effective temperature \(T_e\), and radius \(R\) of each star, along with relevant references, are given in Table 1.

The spectral energy distribution of SS Lep is shown in Figure 1; the plots for BM Gem and 3 Pup are similar. For the sake of comparison, we also display in this figure the scaled spectral energy distributions for VY CMa and the Red Rectangle, as representative of the emission from a “normal” wind (in which the density varies as \(R^{-2}\)), while it is only suspected that BM Gem possesses a dust shell. The dot-dashed line shows the IRAS and submillimeter (Jura & Turner 1998; van der Veen et al. 1994) fluxes for VY CMa scaled by a factor of 0.0109. The long-dashed line shows the IRAS and submillimeter (Jura & Turner 1998; van der Veen et al. 1994) fluxes for the Red Rectangle scaled by a factor of 0.159. The errors are smaller than the squares.

4. THE EVIDENCE FOR LARGE GRAINS

The spectral energy distribution of SS Lep is shown in Figure 1; the plots for BM Gem and 3 Pup are similar. For the sake of comparison, we also display in this figure the scaled spectral energy distributions for VY CMa and the Red Rectangle, as representative of the emission from a “normal” wind (in which the density varies as \(R^{-2}\)), while it is only suspected that BM Gem possesses a dust shell. The dot-dashed line shows the IRAS and submillimeter (Jura & Turner 1998; van der Veen et al. 1994) fluxes for VY CMa scaled by a factor of 0.0109. The long-dashed line shows the IRAS and submillimeter (Jura & Turner 1998; van der Veen et al. 1994) fluxes for the Red Rectangle scaled by a factor of 0.159. The errors are smaller than the squares.
1995) and the stellar parameters in Table 1, the actual Hα luminosity of SS Lep is $2.6 \times 10^{33}$ erg s$^{-1}$, about a factor of 3 less than predicted.

While the observed emission at $\lambda \leq 1.35$ mm is probably produced by dust, the measured fluxes at $\lambda \geq 450$ μm are too strong to be produced from a wind similar to that around VY CMa. Detached shells that are much more extended than the JCMT beam, such as those proposed by van der Veen et al. (1994), could conceivably explain the presence of a large amount of cold dust. However, as explained in more detail in § 5, such detached shell models predict more neutral gas than is observed.

Given that neither a normal wind nor ionized gas can easily explain our measurements, we present an alternative. Let us assume, for simplicity, that the grain emissivity as a function of frequency can be described as a power law $\nu^{\alpha}$. Equivalently, if $Q_{\lambda}$ denotes the ratio of absorption to geometric cross section, then $Q_{\lambda}$ varies as $\nu^{\alpha}$. If the grains are small compared with the wavelength of the light that they emit, then $\alpha \approx 1$, while larger grains might have $\alpha \approx 0$. If $T_{\text{gr}}$ denotes the grain temperature at distance $R$ from the central binary in a steady state where the grain heating, which is determined by the sum of the mean intensity $J_\lambda$ from both stars, is balanced by radiative cooling, then

$$\int Q_{\lambda} J_\lambda(R) d\nu = \int Q_{\lambda} B(T_{\text{gr}}) d\nu.$$  

Therefore, summing over the contribution to $J_\lambda$ by the two stars,

$$T_{\text{gr}}^{(4+\alpha)} = \frac{1}{4} \sum_i T_{\text{gr},i}^{(4+\alpha)} (R_{\text{det}}/R)^2,$$  

where $T_{\text{gr},i}$ and $R_{\text{det},i}$ are the effective temperature and radius, respectively, of the illuminating stars in the central binary.

To compare the predictions of this simple model, we expect for optically thin observations at two different frequencies that

$$F_{\nu,1}/F_{\nu,2} = (\nu/\nu_0)^{\alpha} [B(\nu_1, T_{\text{gr}})/B(\nu_2, T_{\text{gr}})].$$  

We take $F_{\nu,1}(100 \mu m)$ as measured in the large IRAS beam and compare it with $F_{\nu,2}(850 \mu m)$ as measured within the 12" diameter JCMT beam to derive an upper bound for the grain temperature at 6" from the star as expected from equation (3) for both $p = 0$ and $p = 1$. Especially for 3 Pup and SS Lep, if $p = 1$, the predicted value of $T_{\text{gr}}$ of $\sim 120$ K is significantly larger than the inferred value of $\lesssim 45$ K. That is, “small” particles, by themselves, with $p = 1$ cannot be cold enough within the beam of the JCMT to explain the relatively strong submillimeter fluxes. In contrast, models with at least some particles with $p = 0$ can fit the data.

If the grains are spheres of radius $a$, then the requirement that $p = 0$ implies that $a > \lambda/(2\pi R)$. For $\lambda = 850$ μm, $a > 0.1$ mm. If the grains are orbiting the central binary, then, if the disk is optically thin, in order for the gravitational attraction to be larger than the outward force of radiation pressure, then

$$a > 3L_*/(16\pi G M_\star \rho_\star),$$  

where $M_\star$ is the summed mass of the binary and $\rho_\star$ is the matter density of the grains that we take equal to 3 g cm$^{-3}$. For SS Lep, with $M_\star \sim 3 M_\odot$ (see Pols et al. 1991), $a > 0.2$ mm.

5. DUST DISK PARAMETERS

A natural explanation for the presence of large amounts of cold, large grains is that the particles reside in long-lived disks. Measurements of the submillimeter fluxes allow us to estimate the disk parameters. For SS Lep, with $F_{\nu,1}(1350 \mu m) = 25$ mJy, in order to have a brightness temperature less than 1000 K, which is the approximate sublimation temperature of the grains, the inner disk radius must be larger than $7 \times 10^{13}$ cm. This size is greater than the binary separation of 1.5 $\times 10^{13}$ cm if the orbital inclination is 33° (Welty & Wade 1995); the particles must be circumbinary. The inner disk temperature of 450 K derived from the IRAS data (Fajardo-Acosta & Knacke 1995) implies that the inner radius of the disk ($R_{\text{in}}$) is $3 \times 10^{14}$ cm if $p = 0$.

The mass of the grains ($M_{\text{dust}}$) that are emitting at wavelength $\lambda$ can be estimated by using the Rayleigh-Jeans approximation:

$$M_{\text{dust}} = (F_{\nu} \pi^2 D_\lambda^2)/(2kT_{\text{gr}} \chi_{\nu}),$$  

where $D_\lambda$ is the distance from the Earth to the star and $\chi_{\nu}$ is the opacity (in units of cm$^2$ g$^{-1}$) of the material. We adopt $\chi_{\nu}(850 \mu m) \approx 3$ cm$^2$ g$^{-1}$ (Pollack et al. 1994). Assuming an average value of the grain temperature in the telescope beam of 100 K, the mass in dust $M_{\text{dust}}$ is given for each star in Table 1. In every case, $M_{\text{dust}} \gtrsim 5 \times 10^{23}$ g.

In a “detached shell” model similar to that proposed by van der Veen et al. (1994), we assume that $p = 1$, and in Table 1 we list the value of the radius of a detached dust shell ($R_{\text{det}}$) required for the grains to be as cold as the temperature $T_{\text{meas}}$ to account for the observed value of $F_{\nu,1}(850 \mu m)/F_{\nu,1}(100 \mu m)$. The values of $R_{\text{det}}$ are much larger than the projected radius of the JCMT beam ($R_{\text{JCMT}}$) for observations at 850 μm. Therefore, presuming that the JCMT observations have missed most of the submillimeter fluxes from the objects, we estimate the mass of the dust in such a hypothetical detached shell ($M_{\text{dust, det}}$) by the expression $M_{\text{dust, det}} = M_{\text{dust, det}}(100/T_{\text{meas}}) \times (R_{\text{det}}/R_{\text{JCMT}})^2$, where $M_{\text{dust, det}}$ is derived from equation (5), and we assume the dust emits at temperature $T_{\text{meas}}$ instead of 100 K. The total mass of gas in the detached shell ($M_{\text{gas, det}}$) is probably 100$M_{\text{dust, det}}$, and the results for $M_{\text{dust, det}}$ are shown in Table 1. The inferred masses in the hypothetical detached shell for SS Lep and 3 Pup are near 2 and 80 $M_\odot$, respectively. If the detached shell is composed of atomic hydrogen, then we would expect a broad absorption line at Lyα since the line photons that are “scattered” in the damping portion of the line profile ultimately are absorbed by dust grains. In fact, for SS Lep, Blondel et al. (1993) report emission at Lyα within 2 Å of line center. With $\tau(2 Å) = 1.1 \times 10^{-26}N(\text{H})$ (Diplas & Savage 1994), where $N(\text{H})$ is the gas column density through the detached shell, or $N(\text{H})_{\text{det}} = M_{\text{det}}/(4\pi \chi_{\nu}^2 R_{\text{det}}^2)$, where $m_\text{H}$ is the mass of a hydrogen atom, then with an estimate that $\tau(2 Å) < 1$, we find that $M_{\text{det}} < 0.30 M_\odot$, nearly a factor of 10 smaller than required. The absence of CO emission toward SS Lep (Jura & Kahane 1999) argues against much H$_2$ being present. It seems unlikely that there are sufficiently massive detached shells around SS Lep and 3 Pup to explain the strong submillimeter continuum emission.

6. WIND FROM THE DISK?

Above, we have suggested that the fluxes at $\lambda > 100$ μm are produced by large particles in an orbiting disk. Here we suggest that the fluxes produced at $\lambda \leq 100$ μm may be produced by
winds from these disks. At least for SS Lep, the M-type companion probably is too warm, and its luminosity is too low to have a stellar wind with enough dust to account for the infrared fluxes detected by IRAS. The red giant in SS Lep has a spectral type of M4 (Welty & Wade 1995) while in symbiotic systems with large amounts of dust, and the cool mass-losing red giant stars usually are type M6 or later (Kenyon, Fernandez-Castro, & Stencel 1988; Murset & Schmid 1999). Also, in Figure 2, we display $F_{\nu}(12 \mu m)/F_{\nu}(2.2 \mu m)$ versus $M_k$ for all the red giants in the Bright Star Catalog with $(B-V) \geq 1.5$ mag for which distances are measured with Hipparcos and for which the infrared fluxes are reported in the standard catalogs listed in the figure caption. Most of the stars display a value for this ratio that is characteristic of their photospheric emission. The stars with a $12 \mu m$ excess all have $M_k < -6.5$ mag, while SS Lep has $M(K) = -5.9$. Furthermore, even the stars with $M_k < -6.5$ mag have values of $F_{\nu}(12 \mu m)/F_{\nu}(2.2 \mu m)$ less than that for SS Lep.

The source of the wind could be grain-grain collisions by the large particles in the disk that may produce small particles that are driven out of the system by radiation pressure as they absorb and reprocess the light from the central star. In this picture, the mass-loss rate in a disk wind ($\dot{M}_{\text{wind}}$) can be written as (Jura et al. 2000)

$$\dot{M}_{\text{wind}} = \frac{(L_{16}/L_\ast)(2\pi R_{\text{in}} L_\ast)/(c\chi))^{1/2}}{\chi},$$

where $(L_{16}/L_\ast)$ represents the fractional infrared excess radiated by the stellar wind and $\chi$ is the average optical opacity of the small grains in the wind. For all three stars in Table 1, if we assume that the IRAS fluxes are produced by dust in the wind, then $(L_{16}/L_\ast) \sim 0.1$. We adopt $R_{\text{in}} = 3 \times 10^4$ cm for SS Lep and assume that $R_{\text{in}}$ scales as $L_{16}^{3/2}$ for the other two stars. Finally, $\chi \approx 2.5 \times 10^3$ cm$^{-2}$ g$^{-1}$ (Jura et al. 2000). With these parameters, values of $\dot{M}_{\text{wind}}$ are given in Table 1; the minimum value is $5 \times 10^{-17}$ g s$^{-1}$. The nominal lifetime of the disk ($t_{\text{disk}}$) equals $M_{\text{disk}}/\dot{M}_{\text{wind}}$ and, as listed in Table 1, is between $10^3$ and $10^4$ yr. These are minimum ages because mass may be stored in particles $\gg 0.01$ cm that are not detected in the submillimeter measurements. In a disk with a lifetime of 1000 yr and a radius of $3 \times 10^{14}$ cm, particles as large as 0.01 cm in radius can grow by coagulation (see Jura et al. 2000). The evidence for grain evolution around SS Lep is that its 10 $\mu m$ silicate feature is unusually broad and may indicate the presence of crystalline silicates (Fajardo-Acosta & Knacke 1995), a possible signature of a long-lived disk (Molster et al. 1999).

7. CONCLUSIONS

We have detected millimeter and submillimeter continuum emission from two evolved binaries, SS Lep and 3 Pup, and also possibly from BM Gem:

1. This continuum is probably produced by emission from dust colder than $\sim 70$ K lying within 6$^\circ$ of the star and can be explained if the dust particles are at least as large as 0.1 mm in radius.

2. We propose that there are circumbinary orbiting disks of at least $5 \times 10^{19}$ g and that the “large” particles have grown by coagulation in this disk. These disks may have winds with mass-loss rates of $\sim 5 \times 10^{-17}$ g s$^{-1}$ and lifetimes $\geq 2000$ yr.

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