A FLARED, ORBITING, DUSTY DISK AROUND HD 233517

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ABSTRACT

We find that the infrared excess around HD 233517, a first-ascent red giant, can be explained naturally if the star possesses an orbiting, flared, dusty disk. We estimate that the outer radius of this disk is ∼45 AU and the total mass within the disk is ∼0.01 $M_\odot$. We speculate that this disk is the result of the engulfment of a low-mass companion star that occurred when HD 233517 became a red giant.

Subject headings: circumstellar matter — stars: mass loss

1. INTRODUCTION

The evolution of dust disks into large solid bodies such as asteroids, planets, and comets is of central importance in astronomy. While it is usually assumed that such disks are primordial and associated with young stars, some binary systems such as the Red Rectangle apparently create orbiting reservoirs of gas and dust during their post main-sequence evolution (see Waters et al. 1993; Jura & Kahane 1999). To date, there are only a few good candidate systems for orbiting dusty circumstellar material around evolved stars, and therefore every example of this phenomenon is worth studying. Here we propose that the puzzling infrared excess around HD 233517, a first-ascent red giant, can be understood as resulting naturally from a flared, orbiting disk.

Attention was originally drawn to HD 233517 because it is a K-type star ($m_V = 9.72$ mag) that is an *IRAS* source with an unusually large fractional infrared excess ($L_{\rm IR}/L_* \sim 0.06$; Sylvester, Dunkin, & Barlow 2001) produced by cold grains ($T \sim 100$ K), and it was thought to be an example of the Vega phenomenon—a main-sequence star with dust (Walker & Wolstencroft 1988). However, detailed spectroscopic studies strongly suggest that HD 233517 is a first-ascent red giant with a luminosity near 100 $L_\odot$ (Fekel et al. 1996; Balachandran et al. 2000; Zuckerman 2001). While infrared excesses are common around second-ascent red giants on the asymptotic giant branch with luminosities in excess of 1000 $L_\odot$ (see, for example, Habing 1996), relatively few first-ascent red giant stars with their lower luminosities have detectable infrared excesses (Judge, Jordan, & Rowan-Robinson 1987; Zuckerman, Kim, & Liu 1995). HD 233517 has a uniquely high value of $L_{\rm IR}/L_*$ among first-ascent red giants where this ratio is generally less than 10^{-3} (Zuckerman et al. 1995). It is unlikely that HD 233517 is a pre–main-sequence star since it does not lie near any known region of star formation and since it lies far from the location of young stars in the H-R diagram (Fekel et al. 1996; Balachandran et al. 2000). Also, HD 233517 appears to be similar to a few other K giants that rotate rapidly, have strong lithium lines, a detectable far-infrared excess, and are definitely post–main-sequence since, at least in the case of PDS 365, the carbon isotope ratio, $^{12}{\rm C}/^{13}{\rm C}$, is approximately 12 (Drake et al. 2002).

Three models to explain infrared excesses around first-ascent red giants are (1) dust is being produced by mass loss, (2) nearby interstellar dust is illuminated accidentally by the red giant, and (3) the dust is orbiting (see Jura 1999; Kalas et al. 2002). The fraction of red giants that display true dust excesses is uncertain and controversial (Jura 1990, 1999; Plets et al. 1997; Kim, Zuckerman, & Silverstone 2001). In any case, since ground-based imaging shows that the 10 μm excess is physically associated with HD 233517 (Skinner et al. 1995; Fisher et al. 2000), at least for this particular star, the dust producing the infrared excess is either orbiting or expanding away from the star. For some other stars, the infrared excess has been resolved with the *Infrared Space Observatory* and, in these objects, the dust is probably not orbiting (Kim et al. 2001).

There are difficulties with the model that HD 233517 is currently losing enough mass to produce the observed infrared excess. As with other first-ascent red giants with dust, the infrared spectrum of HD 233517 peaks near 60 μm. This spectral energy distribution is characteristic of cool material and is very different from that associated with a continuous mass-loss rate in which there is a substantial amount of dust near a temperature of 1000 K (see, for example, Sopka et al. 1985). One possibility is that the mass-loss rate from HD 233517 is episodic and, currently, the star is not expelling much matter. However, as noted by Jura (1999), the characteristic timescale for the dust to expand around a first-ascent red giant to its inferred location may be less than 20 yr. There is no evidence for recent infrared variability of this star, although the star does exhibit a full-amplitude optical variation of 0.02 mag with a 47.9 day period, which may be caused by star spots rotating in and out of the view (Balachandran et al. 2000).

Since the dust around HD 233517 may not be carried in a wind, we consider models in which the dust is orbiting the star. One scenario is that the dust around HD 233517 is simply left over from the main-sequence phase. However, a major difficulty with this model is that the fractional infrared excess around HD 233517, $L_{\rm IR}/L_*$ of 0.06, is much larger than that found for even the dustiest main-sequence stars such as β Pic and HR 4796, where $L_{\rm IR}/L_*$ is $(2-4) \times 10^{-3}$ (Zuckerman 2001).

Here we speculate that HD 233517 had a low-mass companion that was engulfed when it became a red giant. Although uncertain, the engulfment of this companion could have led to the ejection of an equatorial ring of orbiting material (see Taam & Sandquist 2000; Spruit & Taam 2001). As discussed by Pringle (1991), after this ring is

created, the matter expands under the action of tidal torques that transfer angular momentum from the binary into the circumstellar material, which thus evolves into an extended disk. Although not required in Pringle's model, it is possible that in this dense equatorial ring, dust grains formed. We suggest that the structure of the circumstellar system is described by the models of Chiang & Goldreich (1997) for passive, orbiting disks that flare in response to the illuminating radiation. Below, we present details of this idealized model.

2. THE DISK AND THE STAR

2.1. *Stellar Parameters*

First, we list our assumed parameters for the star. Following Balachandran et al. (2000), we adopt a distance (D_*) of 620 pc, an effective temperature (T_*) of 4475 K, a radius (R_*) of 1.1×10^{12}, cm and a luminosity of 100 $L_\odot$. We assume that the mass of the star (M_*) is approximately 1 $M_\odot$, consistent with the star's location on the H-R diagram and measured surface gravity (Balachandran et al. 2000). The rotational velocity of the star is $v \sin i = 17.6$ km s^{-1}, which implies that if the star rotates as a solid body and if the moment of inertia of the star is $0.1 M_* R_*^2$ (taken from Schwarzschild 1958), then the angular momentum of the star is at least 4×10^{50} g cm^2 s^{-1}.

2.2. *Predicted Infrared Emission*

Dust is required to explain the emission from HD 233517 for $\lambda \geq 10$ μm (see Skinner et al. 1995). Here we use the model of an opaque, flared disk that is locally in vertical hydrostatic equilibrium (Chiang & Goldreich 1997). In this model, the temperature (T_{disk}) as a function of distance from the star (R) is (see Jura, Chen, & Plavchan 2002)

$$T_{\text{disk}} = \left(\frac{1}{7}\right)^{2/7} \left(\frac{R_*}{R}\right)^{3/7} \left(\frac{2k_B T_* R_*}{GM_* \mu}\right)^{1/7} T_* , \quad (1)$$

where k_B is Boltzmann's constant, G is the gravitational constant, and μ is the mean molecular weight of the gas. Here we assume that the gas is primarily H$_2$ with [He]/[H$_2$] = 0.2 so that $\mu = 3.9 \times 10^{-24}$ g. In view of the many uncertainties and to be consistent with inferences for disks around pre–main-sequence stars (Chiang et al. 2001), we assume a simple model in which the half-thickness of the vertically isothermal disk is taken equal to the parameter, h, in Jura et al. (2002), which is a factor of $(2)^{1/2}$ larger than h in Chiang & Goldreich (1997), which characterizes the Gaussian density distribution above the plane.

Since the disk is opaque, we can determine the flux from the source (F_ν) by

$$F_\nu = \frac{2 \pi \cos i}{D_*^2} \int_0^{R_{\text{out}}} B_\nu(T_{\text{disk}}) \, R \, dR , \quad (2)$$

where R_{out} denotes the outer boundary of the disk and where the temperature is T_{out}. For simplicity, we assume a sharp outer boundary, although an exponential decay would be more realistic (see Jura et al. 2002). It is convenient to introduce the dimensionless parameter, x, as follows:

$$x = \frac{h\nu}{k_B T} . \quad (3)$$

From equations (1) and (2),

$$F_\nu = \frac{28\pi}{3} \frac{R_*^2 \cos i}{D_*^2} \left(\frac{k_B T_*}{h\nu}\right)^{5/3} \frac{(k_B T_*)^3}{(hc)^2} \left(\frac{2k_B T_* R_*}{49G \, M_* \mu}\right)^{2/3}$$
$$\times \int_0^{x_{\text{out}}} \frac{x^{11/3}}{e^x - 1} \, dx . \quad (4)$$

At high frequencies with $x_{\text{out}} > 10$, the observed flux is insensitive to the outer boundary condition since the integral in equation (4) is approximately 15. The spectrum is predicted to vary as $\nu^{-5/3}$. At low frequencies where $x_{\text{out}} < 2$, we may rewrite equation (4) to find that

$$F_\nu = \frac{28\pi}{11} \frac{R_*^2 \cos i}{\lambda^2 D_*^2} \left(\frac{T_*}{T_{\text{out}}}\right)^{11/3} \left(\frac{2k_B T_* R_*}{49GM_* \mu}\right)^{2/3} k_B T_* . \quad (5)$$

If the disk is opaque, then at low frequencies, F_ν varies as ν^2.

For the data in the *IRAS* Faint Source Catalog, between 12 and 60 μm, F_ν varies as $\nu^{-1.70}$, in good agreement with the prediction that F_ν should vary as $\nu^{-1.67}$. Furthermore, with $x_{\text{out}} \gg 1$ and $\cos i = 0°$ from equation (4), the predicted value of F_ν (25 μm) is 3.9 Jy, which agrees with the observed value of 3.4 Jy. Thus, without any tweaking, the predictions are close enough to the data that the model should be taken seriously.

Near 60 μm, the slope of the spectral energy distribution turns over. In the flared-disk model, the peak in the spectral energy distribution is governed by the outer boundary of the disk. As shown in Figure 1, we have found that a model with $T_{\text{out}} = 70$ K, which occurs at $R_{\text{out}} = 45$ AU, can reproduce much of the infrared data. However, at 1.35 mm, much more flux is predicted than the observed value of 2.6 ± 1.0,
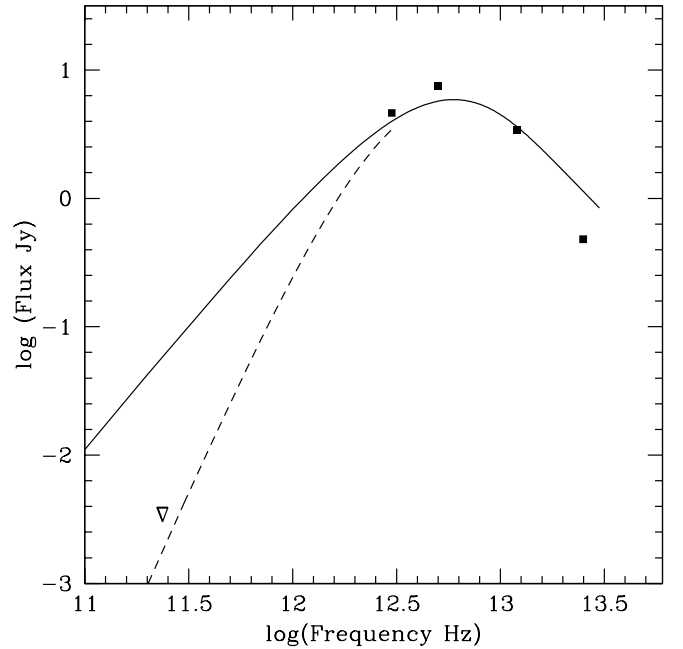

FIG. 1.—Plot of the model spectral energy distribution for HD 233517 compared to observations. *Squares*: Data from *IRAS*. *Triangle*: Upper limit to the flux at 1.35 mm (Sylvester et al. 2001). *Solid line*: Model for the opaque, flared disk. *Dashed line*: Modification to this model if the outer portion of the disk becomes optically thin at $\lambda > 100$ μm as described in the text.

which is conservatively interpreted as a 3 σ upper limit of 3 mJy by Sylvester, Dunkin, & Barlow (2001). A possible resolution of this discrepancy is discussed below.

2.3. Predicted Millimeter Continuum Emission

The flared-disk model drastically overestimates the flux at 1.35 mm. It is observed that between 1.35 and 100 μm, F_ν varies as $\nu^{2.8}$, which suggests that at least at the longer wavelength, the system is optically thin. If the circumstellar dust particles are smaller than 100 μm in diameter, then the opacity at 1.35 mm is probably considerably smaller than the opacity at 100 μm. Although the composition and size distribution of the dust particles are unknown, we adopt parameters representative of circumstellar silicates from Ossenkopf, Henning, & Mathis (1992) and Pollack et al. (1994). Thus, we take $\chi_\nu(100\ \mu m) = 25$ cm^2 g^{-1}, and for $\lambda > 100\ \mu$m, we assume that χ_ν scales as ν^2 so that $\chi_\nu(1.35\ \text{mm}) = 0.14$ cm^2 g^{-1}.

To calculate the flux for the optically thin regime, we need to describe the mass distribution. If Σ denotes the total dust surface density of the disk, then we approximate the model of Pringle (1991) for a circumbinary disk by assuming that all the matter is confined within angular radius ϕ_{out}, where $\phi = R/D_*$, and that within this region,

$$\Sigma = \Sigma_0 \left(\frac{\phi_{\text{out}}}{\phi}\right)^{3/2} . \tag{6}$$

With this description, if M_{dust} denotes the mass of dust in the disk, then

$$\Sigma_{\text{out}} = \frac{M_{\text{dust}}}{4\pi R_{\text{out}}^2} . \tag{7}$$

The flux from the disk, F_{disk}, is

$$F_{\text{disk}} = \cos i \int_0^{\phi_{\text{out}}} 2\pi\phi\, d\phi\, B_\nu(T) \left[1 - \exp^{-\chi_\nu \Sigma_{\text{dust}}(\phi)/\cos i}\right] . \tag{8}$$

We evaluate equation (8) for the condition that at $R = R_{\text{out}}$ (or 45 AU), $\Sigma_{\text{out}} = 0.04$ g cm^{-2}. As discussed below, this value of Σ_{out} is chosen so that the disk is opaque at 100 μm at its outermost region. The results are shown in Figure 1. With the revised model, we see that the predicted flux at 1.35 mm is consistent with the upper limit reported by Sylvester et al (2001).

2.4. Predicted CO Emission

The flared disk model requires that gas be in hydrostatic equilibrium vertical to the orbiting plane of the system. We can estimate the expected amount of CO emission from HD 233517 if the gas and grain temperatures are equal to each other. First,

$$T = T_{\text{out}} \left(\frac{\phi_{\text{out}}}{\phi}\right)^{3/7} . \tag{9}$$

If the gas is optically thick, then in a telescope of beam size (Ω_{tel}) the observed brightness temperature (T_{obs}) is

$$T_{\text{obs}} = \cos i \int_0^{\phi_{\text{out}}} \frac{2\pi\phi T(\phi)\, d\phi}{\Omega_{\text{tel}}} = \frac{14\pi}{11} \frac{T_{\text{out}} \phi_{\text{out}}^2 \cos i}{\Omega_{\text{tel}}} . \tag{10}$$

Within the 10$''$5 beam of the IRAM telescope, Jura & Kahane (1999) placed a 1 σ upper limit to the CO $J2 \rightarrow 1$ emission line of 29 mK. In our model, $\phi_{\text{out}} = 0''073$, and the predicted brightness temperature in this line is 17 mK. Thus, the model is consistent with the observed upper limit to the CO line emission.

2.5. Disk Mass and Angular Momentum

We derive a minimum mass of the disk from the criterion that our model requires the disk to be opaque even at $R = R_{\text{out}}$ at 100 μm or $\Sigma_{\text{out}} \chi_\nu(100\ \mu m) > 1$. With $\chi_\nu(100\ \mu m) = 25$ cm^2 g^{-1}, this implies that $\Sigma_{\text{out}} = 0.04$ cm^2 g^{-1}. Therefore, from equation (7), the mass of the dust in the disk is 2×10^{29} g. If the gas-to-dust ratio is 100, the total disk mass is $\sim$0.01 $M_\odot$.

Another important parameter is the disk angular momentum, J. With a sharp outer boundary and the surface density variation given by equation (6), we may write

$$J = \frac{M_{\text{disk}}}{2} \sqrt{GM_* R_{\text{out}}} . \tag{11}$$

We therefore estimate a total angular momentum of the disk of 3×10^{51} g cm^2 s^{-1}, which is larger than the total angular momentum of the star estimated above to be $\geq 4 \times 10^{50}$ g cm^2 s^{-1}.

3. DISCUSSION

We have found that the infrared fluxes from HD 233517 are explained naturally with the simple flared-disk model. The origin of this disk is uncertain. One possible model to account for both the creation of a disk and the unusually high rotation speed of the red giant is that while on the main sequence, HD 233517 had a companion at an orbital separation of about 1×10^{12} cm (see Soker, Livio, & Harpaz 1984). We speculate that when HD 233517 became a red giant, it engulfed this companion with the consequences of both creating an orbiting ring of circumbinary matter and spinning up the primary star. With the parameters derived above, the total angular momentum of HD 233517 and its associated disk is 3×10^{51} g cm^2 s^{-1}. This amount of angular momentum could have been supplied by a companion star of 0.12 $M_\odot$ in a circular orbit of radius 1.1×10^{12} cm.

HD 233517 is a lithium-rich star (Fekel et al. 1996; Balachandran et al. 2000). While single-star models might explain this result (de la Reza et al. 1997; Jasniewicz et al. 1999; Charbonnel & Balachandran 2000), in our picture, this lithium enrichment results because the system was a binary. The absence of ^{6}Li argues against the simple idea that incorporation of lithium from a planet or low-mass companion into the envelope of the star (Balachandran et al. 2000) can explain the observed abundance of this element, but the capture of a companion might have led to an episode that stimulated interior mixing of lithium to the surface (Denissenkov & Weiss 2000).

With a value of $L_{\text{IR}}/L_* > 10^{-2}$, HD 233517 is a distinctive red giant. In the sample of Zuckerman et al. (1995) of more than 40,000 of the nearest luminosity class III giants, the highest value of L_{IR}/L_* is 10^{-3}. Although the statistics are poor, perhaps only 10^{-4} of all first-ascent red giants have as much circumstellar opacity as does HD 233517. We suggest that HD 233517 is unusual for two reasons. First, according to Duqennoy & Mayor (1991), only $\sim$2% of all

solar-mass main-sequence stars have detectable companions with orbital periods near 10 days. Such binaries are the kinds of systems that can evolve into a red giant with a disk as substantial as the one found around HD 233517. Furthermore, once the disk is formed, it must have a limited lifetime. The massive dusty disk around HD 233517 may evolve in a fashion somewhat like disks around pre–main-sequence stars. For A-type stars that have luminosities somewhat less than that of HD 233517, the lifetime of the disk as a system with $L_{IR}/L_* > 10^{-2}$ is near 3×10^6 yr, although some small amount of dust could linger for as long as 4×10^8 yr (see Habing et al. 1999; Spangler et al. 2001). Since the lifetime of a 1 $M_\odot$ red giant as it evolves from 10 $L_\odot$ to its maximum luminosity of 2700 $L_\odot$ is $\sim 2 \times 10^8$ yr (Girardi et al. 2000), only $\sim$1% of the disks around red giants might have L_{IR}/L_* as large as 10^{-2}. Given these two

considerations, it is not too surprising that a system like HD 233517 occurs among first-ascent red giants with a frequency of perhaps 10^{-4}. A plausible explanation for the inferred decrease of L_{IR}/L_* with time is that the dust particles coalesce into larger bodies.

4. CONCLUSIONS

We have modeled the currently available infrared data for HD 233517 and find that the observations can be explained naturally by a flared, orbiting disk of mass $\sim$0.01 $M_\odot$ and outer radius of $\sim$ 45 AU. We speculate that this disk was created by the engulfment of a low-mass stellar companion.

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