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POLYCYCLIC AROMATIC HYDROCARBONS ORBITING HD 233517, AN EVOLVED OXYGEN-RICH RED GIANT[1]

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ABSTRACT

We report spectra obtained with the *Spitzer Space Telescope* in the $\lambda = 5$–35 μm range of HD 233517, an evolved K2 III giant with circumstellar dust. For $\lambda > 13$ μm, the flux is a smooth continuum that varies approximately as $\nu^{-5/3}$. For $\lambda < 13$ μm, although the star is oxygen-rich, PAH features produced by carbon-rich species at 6.3, 8.2, 11.3, and 12.7 μm are detected along with likely broad silicate emission near 20 μm. These results can be explained if there is a passive, flared disk orbiting HD 233517. Our data support the hypothesis that organic molecules in orbiting disks may be synthesized in situ as well as having been incorporated from the interstellar medium.

Subject headings: circumstellar matterstars: general

1. INTRODUCTION

We study dusty circumstellar disks in order to understand better the origin and evolution of planets and stars. Analogous to young stellar objects, disks around evolved stars such as the Red Rectangle are important in the angular momentum budget of the system and also may be sites where planets form, as occurred around the pulsar PSR 1215+12 (Wolszczan & Frail 1992). Here we report data obtained with the Infrared Spectrograph (IRS; Houck et al. 2004) on the *Spitzer Space Telescope* (Werner et al. 2004) that provide supporting evidence for the hypothesis (Jura 2003) that the evolved red giant HD 233517 (K2 III) possesses an orbiting disk.

About 10^5 red giants were detected with the *Infrared Astronomical Satellite* (*IRAS*). While asymptotic giant branch (AGB) stars with luminosities larger than 10^3 $L_\odot$ usually have large enough mass-loss rates to produce substantial infrared excesses (see, e.g., Sopka et al. 1985), the less powerful first-ascent red giants with luminosities near 100 $L_\odot$ typically do not have measurable infrared excesses. Even when present, the typical fractional excess is only between 10^{-4} and 10^{-3} of the star's luminosity (Zuckerman et al. 1995) and, at least in some cases, actually may be produced by an interstellar cirrus rather than mass loss (Kim et al. 2001). Only a handful of class III red giants with larger excesses are known; a well-studied example is HD 233517 with a luminosity of 90 $L_\odot$ and a fractional excess of ~0.06 (Sylvester et al. 2001). Identified as anomalous in the *IRAS* database (Walker & Wolstencroft 1988), initially, it was thought to be a main-sequence star (Skinner et al. 1995). Although its parallax is not measured, high-resolution optical spectroscopy shows that it is a red giant (Fekel et al. 1996; Balachandran et al. 2000 Zuckerman 2001). Furthermore, HD 233517 is likely to be post–main-sequence rather than pre–main-sequence because it is spatially isolated from any known region of star formation, does not fall on any theoretical tracks in the H-R diagram for pre–main-sequence stars, and shows an abundance of lithium of [Li]/[H] $= 1.7 \times 10^{-8}$ about an order of magnitude greater than the standard interstellar value of 2×10^{-9} (Anders & Grevesse 1989, Howarth et al. 2002). This large abundance of lithium can be explained by models of surface mixing of processed material in some models of post–main-sequence evolution (see, e.g., Denissenkov & Weiss 2000 and Denissenkov & Herwig 2004) but not by current models for pre–main-sequence stars.

HD 233517 has $v \sin i = 17.6$ km s^{-1} (Balachandran et al. 2000), which is substantially greater than the typical rotational speed of a class III red giant of $\leq$5 km s^{-1} (de Medeiros & Mayor 1995; Gray & Pallavicini 1989; Schrijver & Pols 1993) but smaller than the maximum possible of ~35 km s^{-1}. There are a few other first-ascent red giants that also have marked infrared excesses, distinctively high lithium abundances, and unusually rapid rotation (see, e.g., Drake et al. 2002 and Reddy & Lambert 2005). Any model describing HD 233517 may also pertain to these stars.

Previously, Jura (2003) has argued that the infrared excess around HD 233517 is unlikely to be produced by a recent outflow in a stellar wind. For most red giants that are currently losing mass, F_ν typically varies as $\nu^{1.5}$ for $\lambda > 10$ μm (see, e.g., Sopka et al. 1985). However, for HD 233517, the *IRAS* fluxes between $\lambda = 13$ μm and $\lambda = 60$ μm vary approximately as $\nu^{-5/3}$, a spectral energy distribution that can be naturally modeled with a passive, flared, orbiting disk. Also, the CO radio emission from the system is probably undetected (Jura & Kahane 1999; Dent et al. 2005). In contrast, the winds from mass-losing red giants typically are easily detectable CO sources (see, e.g., Olofsson et al. 1993). Here we report additional evidence in support of the view that the infrared excess of HD 233517 is produced by orbiting dust.

Our study of HD 233217 can help us understand other circumstellar disks. For example, there is controversy about the origin of organic molecules in the early solar system. The usual view is that most of the carbonaceous material was incorporated as carbon-rich compounds from the interstellar medium and then further processed (Ehrenfreund & Charnley 2000; Kerridge 1999). However, a contrary view is that even in the oxygen-rich solar nebula, Fischer-Tropsch catalysis on the surface of metal

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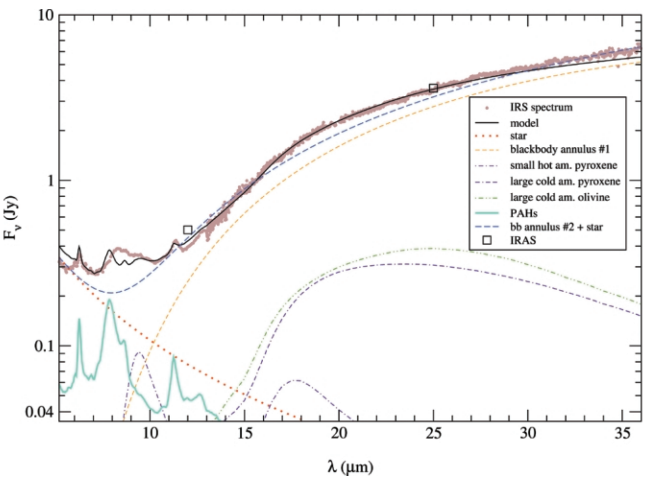

FIG. 1.—IRS spectrum of HD 233517 and *IRAS* data points shown as open squares. The dashed line for bb annulus #2 + star denotes the preliminary model with only a flared passive opaque disk described in the text. The solid line shows the final model that includes both a somewhat smaller opaque disk (blackbody annulus #1) and a set of optically thin smaller particles including pyroxene and olivine silicate grains with "large" and "small" defined in the text and the PAH emission scaled from HD 34282.

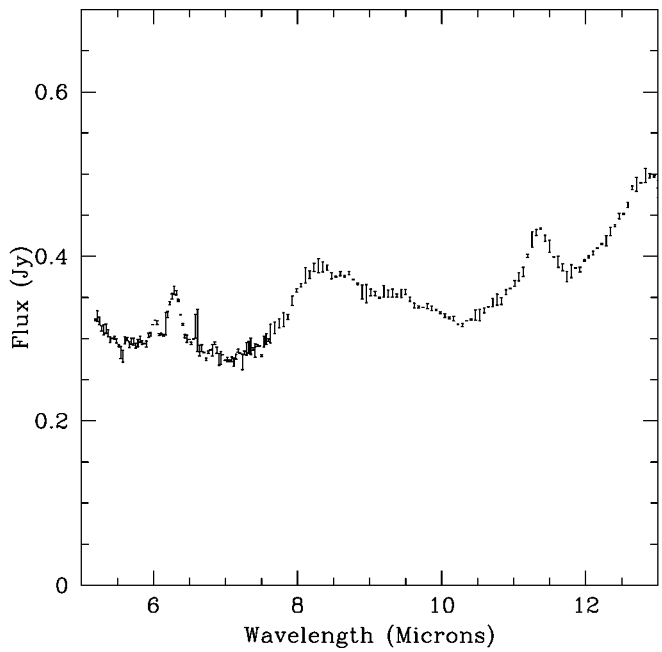

FIG. 2.—Expanded version of the IRS spectrum of HD 233517 that shows the emission features and their profiles together with the 1 σ errors. The apparent emission near 6.5 μm is not real.

grains at $T > 400$ K was an important route for the synthesis of carbon-rich molecules (Kress & Tielens 2001; Zolotov & Shock 2001). Alternatively, gas-phase synthesis of such molecules may be important (Morgan et al. 1991). Since the disk around HD 233517 is free of interstellar contamination, it can serve as an indirect test of these models.

2. OBSERVATIONS

We observed HD 233517 on 2004 March 26 with the IRS; the data are labeled as AOR 3586048. We operated the observatory in IRS Spectral Mapping mode where a 2 × 3 raster (spatial × dispersion) centered on the star is performed. The slit positions were separated by half of the slit width in the dispersion direction and by a third of the slit length in the spatial direction. We observed this object in both orders of IRS Short-Low, SL (5.3–15 μm, $\lambda/\Delta\lambda \sim 90$). Additionally, we observed this source in all orders of IRS Short-High, SH (10–20 μm, $\lambda/\Delta\lambda \sim 600$) and all orders of IRS Long-High, LH (20–40 μm, $\lambda/\Delta\lambda \sim 600$).

We reduced the spectra using the Spectral Modeling, Analysis, and Reduction Tool (SMART; Higdon et al. 2004). We began with the data product from the *Spitzer* Science Center IRS calibration pipeline version S11.0.2 labeled "BCD," which was already processed with the stray light correction and with the flat-field correction of the final Basic Calibrated Data product. The spectra for all modules came from reducing the data from the center map positions. For the SL data, we first subtracted sky by subtracting the off order of the same nod. We then extracted the spectra as a point source for each nod position with a column extraction about 4 pixels wide in the spatial direction. The spectra of each nod were then divided by the nodded spectrum of our identically extracted photometric low-resolution standard star α Lac and then multiplied by the standard‘s template spectrum (Cohen et al. 2003). SH and LH data were extracted using a full-slit extraction without any sky subtraction due to a lack of off-order sky positions for the high-resolution modules. Each nod of the extracted spectra was then divided by the corresponding nod of the identically extracted high-resolution photometric standard star ξ Dra and then multiplied by the template spectrum. We then merged each nod of SL, SH, and LH to produce two complete spectra, one for each nod, that were subsequently averaged. We estimated the uncertainty to be half the difference between the two nods.

There are some small mismatches in flux between modules that are within our absolute spectrophotometric accuracy of 10%. These mismatches were corrected by scaling the SH and LH modules to match the more reliably calibrated SL. Our reduced spectrum is shown in Figure 1. Longward of 13 μm, the flux is a featureless continuum that rises to the red with a kink near 20 μm. Shortward of 13 μm, there are polycyclic aromatic hydrocarbon (PAH) features at 6.26, 8.24, 11.31, and 12.67 μm. Figure 2 shows a more detailed view of the shorter wavelength portion of the spectrum, and Table 1 summarizes the feature properties. The feature wavelengths are well measured, but the energy carried in each feature is uncertain because we cannot accurately measure the continuum level. A particular uncertainty is that the broad feature that peaks at 8.2 μm may actually be a blend of broad PAH emission (described as type C by Peeters et al. 2002) that extends to 9.2 μm and silicate emission between 9.2 and 10.2 μm. The PAH features carry about 1% of the total excess and thus reradiate less than 0.1% of the total stellar luminosity.

3. MODEL AND INTERPRETATION

In order to model the continuum emission from the disk, we follow Balachandran et al. (2000) and adopt a mass M_* of

TABLE 1
PAH EMISSION FEATURES

Wavelength (μm)	Line Flux (10^{-13} ergs cm^{-2} s^{-1})
6.26 ± 0.019	19 ± 2
8.24 ± 0.037	24 ± 2
11.31 ± 0.022	7 ± 1
12.67 ± 0.031	4 ± 1

1 $M_{\odot}$, a radius R_* of 1.1×10^{12} cm, an effective temperature T_* of 4475 K, and a distance D_* of 620 pc. Following Jura (2003), we assume a passive, flared disk where a well-mixed fluid of gas and dust moves in circular orbits around the central star. At every orbital radius R from the star, the disk is assumed to have a single temperature that is controlled by the balance between radiative heating of the disk from the star and reradiation of the disk in the infrared. The gas and dust temperatures are assumed to be equal to each other. Perpendicular to the plane of the disk, vertical hydrostatic equilibrium is established, and the density distribution is described by a Gaussian with a half-thickness that is greater than the radius of the star.

We first present a preliminary model to fit the continuum labeled bb annulus #2 in Figure 1, and we then describe an improved, final model. If $T_{\rm disk}$ denotes the disk temperature, then

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

where $k_{\rm B}$ is Boltzmann's constant, G is the gravitational constant, and μ is the mean molecular weight of the gas here taken as 3.9×10^{-24} g. The flux at the Earth, F_ν, is

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

To compute F_ν, we need to know the inner and outer boundaries of the disk, $R_{\rm in}$ and $R_{\rm out}$, and the inclination of the disk, i, which we take to equal 0°. Equations (1) and (2) yield

$$F_\nu = \frac{28\pi}{3} \frac{\cos i R_*^2}{D_*^2} \left(\frac{k_{\rm B}T_*}{h\nu}\right)^{5/3} \frac{(k_{\rm B}T_*)^3}{(hc)^2} \left(\frac{2k_{\rm B}T_*R_*}{49GM_*\mu}\right)^{2/3} \times \int_{x_{\rm in}}^{x_{\rm out}} \frac{x^{11/3}}{e^x - 1}\, dx, \quad (3)$$

where $x = h\nu/k_{\rm B}T$. From equation (3), we expect for an infinite disk that F_ν varies as $\nu^{-5/3}$, which matches the data reasonably well for $\lambda > 20$ μm. However, it overpredicts the flux at $\lambda < 20$ μm and also does not match the kink in the spectrum at this wavelength. For our preliminary model to avoid producing too much shorter wavelength radiation, we adopt an inner disk boundary of $R = 2.8$ AU, where $T = 230$ K. In order to account for the continuous rise in the emission to 35 μm, we require that $T_{\rm out} <$ 65 K or that $R_{\rm out} > 50$ AU. Ground-based observations yield an upper limit to the FWHM of the 18.2 μm emission of 0.″41 (Fisher et al. 2003) or a radius of 130 AU. For our preliminary model, we adopt $R_{\rm out} = 150$ AU since the fluxes at $\lambda < 35$ μm are insensitive to the exact value of $R_{\rm out}$. We see in Figure 1 that for $\lambda > 13$ μm, the preliminary model reproduces F_ν to within 20%.

In the final model labeled blackbody annulus #1 in Figure 1, we use a somewhat smaller dust torus by setting $R_{\rm in} = 4$ AU and $R_{\rm out} = 63$ AU, and we add an ensemble of optically thin grains that we picture as suspended in the disk atmosphere above and below the disk midplane. This additional material includes 3×10^{23} g of spherical pyroxene grains with radii of 0.1 μm at a temperature of 300 K, 4.5×10^{25} g of amorphous olivine with radii of 3 μm and a temperature of 130 K, and 4.5×10^{25} g of amorphous pyroxene with radii of 3 μm and a temperature of 130 K. Finally, we scale the PAH emission reported by Sloan et al. (2005) for HD 34282, a Herbig Ae/Be star; the template from this star provided the best match to the PAH features for HD 233517. As shown in Figure 1, the final model reproduces most of the features near 10 μm and also better reproduces the kink in the continuum near 20 μm.

We can estimate indirectly the amount of material in the system. In evaluating equation (3) to estimate the infrared flux from the disk and to produce the spectral fit seen in Figure 1, we assume a gas that is mostly H_2 and He. Presuming that the initial outflow that produced the currently observed disk is typical of mass-losing stars, we adopt a gas-to-dust ratio by mass of 100 and require enough dust to produce the 100 μm *IRAS* flux. With these assumptions, the total gas mass in the disk is ∼0.01 $M_{\odot}$, and the total disk angular momentum is $\sim 3 \times 10^{51}$ g cm^2 s^{-1}, which is too much for a single star of ∼1 $M_{\odot}$ (Jura 2003). Initially, the system must have been a binary.

The PAH emission spectrum that we report here for HD 233517 somewhat resembles the spectra for the Egg Nebula (or RAFGL 2688) and IRAS 13416−6243, in which the 7.7 μm component is absent and the 8.2 μm component is strong and asymmetric to the red (the rare class "C" spectra, reported by Peeters et al. 2002). Both the Nova V705 Cas (Evans et al. 2005) and the pre–main-sequence star HD 135344 (Sloan et al. 2005) also exhibit a pattern of PAH emission in which the 7.7 μm component is relatively weak.

4. DISCUSSION

A striking result in our data is the detection of PAH features in the circumstellar dust around an oxygen-rich star. If the material was recently ejected from HD 233517, it would be mostly composed of silicates as found for almost all winds from oxygen-rich stars with a handful of possible exceptions (Sylvester et al. 1994, 1998; Speck et al. 2000). We interpret the presence of carbon-rich material in the circumstellar matter as evidence against a standard wind model.

One unlikely hypothesis is that there is an unseen secondary star in the system that was once carbon-rich and lost matter that ended up in the disk around HD 233517. Since mass-losing carbon stars on the AGB have luminosities larger than 10^3 $L_{\odot}$ (see, e.g., Olofsson et al. 1993), this hypothetical mass-losing carbon star must now be a white dwarf. The lack of radial velocity variation shows that there does not appear to be any close stellar companion to HD 233517 (Balachandran et al. 2000). If there is a distant white dwarf at an orbital separation of, say, 50 AU, it is conceivable that 1% of its wind was captured by HD 233517 to produce a disk of 0.01 $M_{\odot}$. There are, however, difficulties with the picture of HD 233517 having a distant white dwarf companion. First, this model does not offer an explanation for the very high lithium abundance in HD 233517. Second, this scenario does not require that the mass-gaining star be a red giant, but there are no known main-sequence stars with infrared excesses similar to that of HD 233517. Third, if there is a hot white dwarf in the system near enough to transfer a substantial amount of matter to the red giant, then the system might appear to be symbiotic or might at least display some unusual ultraviolet emission that is not seen.

One possibility is that the PAH material around HD 233517 is the result of a set of Kuiper Belt objects that are rapidly sublimating since the star has become a red giant. A difficulty with this picture is that while comets contain a large amount of organic material, they apparently do not possess many PAHs (see Ehrenfreund & Charnley 2000), although there might be some as yet unidentified chemical pathway to convert the organic material into PAHs. Also, we do not detect strong silicate emission, which is characteristic of comets.

Following Jura (2003), we hypothesize that, while on the main sequence, HD 233517 was a short-period binary. When the more massive star of the pair became a red giant, there was an episode of rapid, unstable, mass transfer with the low-mass secondary spiraling into the primary. When the low-mass companion was engulfed, there was so much angular momentum in the system that mass was equatorially ejected into the immediate surroundings (see, e.g., Counselman 1973, Eggleton & Kiseleva-Eggleton 2002, and Hut 1980). The circumstellar matter subsequently expanded to its current size due to viscosity (see Pringle 1991). Below, we sketch a scenario by which this disk might exhibit a carbon-rich chemistry.

At $T < 1000$ K, the exact temperature depending on the pressure, the thermodynamically preferred states of carbon and oxygen atoms are in the molecules CH_4 and H_2O rather than CO (see, e.g., Burrows & Sharp 1999 and Zolotov & Shock 2001). At a sufficiently low temperature, water and ice droplets form, while CH_4 remains in the gas phase until the temperature drops significantly below 100 K (Boogert et al. 1998). The disk's approach to this thermodynamically predicted state in a sufficiently short time can be facilitated by Fischer-Tropsch (FT) catalysis on the surface of iron grains at phases when the material was warmer than 400 K, as has been suggested to explain the presence of carbonaceous material in meteorites (see, e.g., Kress & Tielens 2001 and Zolotov & Shock 2001). Alternatively, gas-phase chemistry may be important (Morgan et al. 1991). Although detailed models are required, we imagine a scenario somewhat similar to what Willacy (2004) has computed for the role of FT reactions in the outflow from the carbon-rich star IRC +10 216 in which CO and H_2 are converted to H_2O and hydrocarbons. She found that if solid iron grains are formed, then about 0.1% of the CO is converted to water. Since the density in the disk at, say, 10 AU around HD 233517 ($\sim 10^{12}$ cm^{-3}) is so much greater than in the warm region at 10 AU of the wind from IRC +10 216 ($\sim 10^{9}$ cm^{-3}), it is plausible that the FT reactions could effectively convert much of the carbon initially contained in CO into hydrocarbons around HD 233517. Subsequently, perhaps analogous to the atmospheric chemistry in Jupiter (Wong et al. 2003), these simple hydrocarbons could be converted into PAHs. Such a scenario may occur in other environments with metal grains, perhaps accounting for the apparent presence of PAHs in the circumstellar shells around oxygen-rich red supergiants in h and χ Persei (Sylvester et al. 1994). The unusual character of the PAH spectrum of HD 233517 may be a valuable but as yet unexplained clue to understanding the origin of this material in an oxygen-rich disk.

5. CONCLUSIONS

The infrared spectrum of HD 233517 shows emission from PAHs and has a continuum that can be reproduced approximately with a passive, flared, orbiting disk. The data can be explained if the material resides in a long-lived orbiting disk that may have been created when HD 233517 engulfed a companion. The data lend support to the hypothesis that organic molecules in disks may be synthesized in situ as well as having been incorporated from the interstellar medium.

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