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DETECTION OF EXTENDED THERMAL INFRARED EMISSION AROUND THE VEGA-LIKE SOURCE HD 141569

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ABSTRACT

We report the detection of extended IR emission at 10.8 and 18.2 μm around the Vega-like source HD 141569. Mid-IR imaging with OSCIR on Keck II shows emission from dust extending out to 100 AU from the B9.5 Ve star. Our modeling of the dust places an upper limit of ∼2 μm on the diameter of the mid-IR–emitting particles if they are Mie spheres of astronomical silicates. Comparison of our mid-IR images to the near-IR (1.1 μm) NICMOS images of HD 141569 (Weinberger et al. 1999) shows that the mid-IR emission originates at smaller distances from the star than the scattered near-IR light, as also previously observed for the archetype Vega-like source β Pictoris.

Subject headings: circumstellar matter — stars: individual (HD 141569)

1. INTRODUCTION

Vega-like stars are main-sequence stars that exhibit excess radiation at infrared wavelengths. The excess emission is thermal radiation from dust thought to be distributed in a circumstellar disk. The excesses of the four prototype stars of this class of object, α Lyr, α PsA, β Pic, and ϵ Eri, were discovered by *IRAS* (Aumann et al. 1984). More thorough searches of the *IRAS* database, including those by Walker & Wolstencroft (1988), Stencel & Backman (1991), and more recently by Mannings & Barlow (1998), turned up many more examples of stars exhibiting this so-called "Vega phenomenon," including the source HD 141569 that is the subject of this Letter. Since planets are thought to form in the dusty environments around stars, there seems to be a growing consensus that the Vega phenomenon is intimately connected with the occurrence of planetary systems. However, we do not yet know if it is an indicator of forming, already formed, or failed planetary systems.

Here we present new mid-IR observations of the Vega-like star HD 141569 (B9.5 Ve). The status of HD 141569 is, in fact, ambiguous. It is classified as a Vega-like star by some authors (e.g., Sylvester et al. 1996) but as a Herbig Ae/Be star by others (e.g., van den Ancker, de Winter, & Tjin A Djie 1998). The fact that HD 141569 exhibits characteristics of both a pre–main-sequence and a main-sequence object suggests that it may be a transitional star (van den Ancker et al. 1998). For example, HD 141569 fulfills three of the four criteria for a Herbig Ae/Be star put forth by Herbig in his original paper (Herbig 1960). It has a spectral type earlier than F0, there are emission lines present in its spectrum (i.e., Hα and O I at 7772 and 8446 Å), and it is associated with a relatively bright reflection nebula. By themselves, these facts suggest that the source is a member of this class of object. However, the Paschen series is not in emission in HD 141569, which is unusual for a Herbig Ae/Be star (Andrillat, Jaschek, & Jaschek 1990). In addition, HD 141569 exhibits no measurable photometric variation, whereas most (>65%) Herbig Ae/Be stars show variations larger than 0.05 mag (Alvarez & Schuster 1981; Schuster & Guichard 1984). Finally, the ratio of infrared to stellar luminosities for HD 141569 is 8×10^{-3} (Sylvester et al. 1996), comparable to the value $\sim 3 \times 10^{-3}$ for the prototype Vega-like star β Pic but low for a Herbig Ae/Be star. These counterarguments make it difficult to classify HD 141569 as a Herbig Ae/Be star, but they are consistent with its being more evolved, possibly more than 10^7 yr old (van den Ancker et al. 1998).

The possible transitional nature of HD 141569 is reflected in its position in the H-R diagram. HD 141569 has a *Hipparcos*-measured distance of 99 pc and Tycho magnitudes that transform to give $(B-V) = 0.078$ (Sahu et al. 1998). If we assume that the $(B-V)$ color is indicative of interstellar reddening, HD 141569 has an absolute magnitude $M_v = 1.6$ (Weinberger et al. 1999). We can therefore place it on, or very close to, the zero-age main sequence consistent with its being young (Jura et al. 1998). Interestingly, in the H-R diagram HD 141569 lies between the two other Vega-like stars that have well-resolved disks in the optical and/or infrared, β Pic and HR 4796A. This evidence suggests, then, that HD 141569 may be evolving from a Herbig Ae/Be star to a Vega-like star, thereby representing a link between the classes.

In this Letter, we present the results of our imaging of HD 141569 at the Keck II telescope using the Observatory Spectrometer and Camera for the Infrared (OSCIR), the University of Florida mid-IR imager. Section 2 describes our OSCIR observations. In §§ 3.1 and 3.2 we use the observed source size and flux density estimates to investigate the properties of the dust around the source. We compare our results to recent near-IR camera and multiobject spectrometer (NICMOS) observations of the source made by Weinberger et al. (1999) in § 3.3. Section 4 summarizes our conclusions.

2. OBSERVATIONS

Mid-IR observations of HD 141569 using OSCIR were obtained on four separate observing runs between 1998 May 15 and 1999 August 30. Our team detected the extended emission surrounding HD 141569 at Keck on 1998 May 14 and 15. Subsequent observations made at Keck and at the Cerro Tololo Inter-American Observatory (CTIO) Blanco 4 m telescope were used to obtain more accurate flux estimates for the source. The OSCIR system, a mid-IR camera/spectrometer built by the

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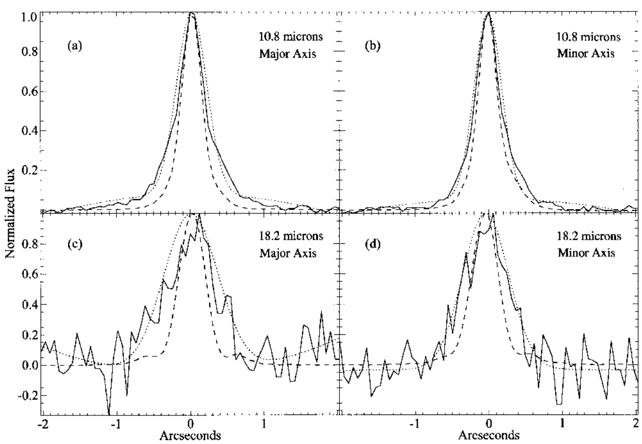

FIG. 1.—Scans through HD 41569 and the PSF star. In all plots, HD 141569 is the solid line, and the PSF star is the dashed line. A Gaussian fit to the HD 141569 data is shown as the dotted line. (*a*) Scan through the major axis (P.A. = 175°) of HD 141569 at 10.8 μm. (*b*) Scan through the minor axis of HD 141569 at 10.8 μm. (*c*) Major axis (P.A. = 175°) scan at 18.2 μm. (*d*) Minor axis scan at 18.2 μm.

University of Florida Infrared Astrophysics Group, uses a 128 × 128 pixel Si:As blocked impurity band detector developed by Boeing.

On Keck, OSCIR has a plate scale of 0″.062 pixel^{-1}, which gives a field of view of 7″.9 × 7″.9. All observations were made using standard chop/nod techniques with an 8″ chopper throw in declination. HD 141569 was observed on two separate occasions at Keck. Images of HD 141569 were obtained in the *N*-band (λ_0 = 10.8 μm, $\Delta\lambda$ = 5.2 μm) and in the IHW 18 band (λ_0 = 18.2 μm, $\Delta\lambda$ = 1.7 μm). The Keck autoguider system was used for all of the Keck observations. On both Keck runs (1998 May and 1999 May), the weather was marginal with light cirrus clouds present during the nights HD 141569 was observed. During postprocessing of the data, chopped image pairs that were obviously compromised by the cirrus were discarded. However, there is still some uncertainty in the photometry of the source and the standard stars, which we take to be ±10%. For most of the observations, this translates into the major component of the uncertainties associated with the flux estimates.

Despite the cirrus, the seeing during the HD 141569 observations was very good. Measurements of the FWHM intensities of comparison stars were approximately 0″.32 and 0″.42 at 10.8 and 18.2 μm, respectively. Quadratic subtraction of the diffraction limits (λ/D) of 0″.22 at 10.8 μm and 0″.37 at 18.2 μm from these values from implies seeing of ∼0″.2–0″.3 in the 10–20 μm spectral region.

On the CTIO Blanco 4 m telescope, OSCIR has a plate scale of 0″.18 pixel^{-1}, with an array field of view of 23″ × 23″. Images of HD 141569 were obtained between 1999 February 28 and March 2 and again on 1999 August 26 in the *N* and IHW 18 filters at CTIO to assist in the flux calibration of the Keck images. We used the standard chop/nod technique during the CTIO observations with a chopper throw of 25″ in declination. These observations were made under generally good sky conditions (i.e., no cirrus).

Our 10.8 μm flux measurements for HD 141569 range from 260 to 429 mJy, while the 18.2 μm measurements range from 528 to 723 mJy. We combined all of the measurements from the different nights into a single flux estimate for each wavelength using a variance-weighted mean. The resulting flux estimates are 318 ± 16 mJy in the *N* band and 646 ± 35 mJy in the IHW 18 band. These flux estimates are somewhat low compared to other measurements of the source including those by Sylvester et al. (1996). Our OSCIR measurements are 68% and 58% of the Sylvester estimates at 10.8 and 18.2 μm, respectively. However, the ratio of the fluxes ($F_{10.8}/F_{18.2}$) presented here is very consistent with the Sylvester et al. (1996) flux ratio. As we will see in § 3.2, it is primarily the flux ratio ($F_{10.8}/F_{18.2}$) that allows us to place an upper limit on the size of the mid-IR–emitting grains around HD 141569.

In addition to the emission from the dust, the measured fluxes contain mid-IR radiation emitted by the photosphere of the central star. To remove this photospheric emission, we estimated the mid-IR flux densities of HD 141569 (B9.5 Ve) by normalizing the spectral energy distribution of Vega (A0 V) to the *K*-band (2.2 μm) flux density of HD 141569 measured by Sylvester et al. (1996). This method implies a photospheric flux density of 72 mJy at 10.8 μm (22% of the total flux at this wavelength). At 18.2 μm, the photosphere emits 23 mJy (4% of the total flux). The photosphere-subtracted, variance-weighted flux estimates and associated errors are 246 ± 16 mJy at 10.8 μm and 623 ± 35 mJy at 18.2 μm.

3. DISCUSSION

3.1. *Source Size*

The extended emission from HD 141569 is seen as an elongation of the source at P.A. = 175° ± 10°. The diameter of the major axis of the emission at 10.8 μm is ∼2″.2, which corresponds to ∼215 AU. At 18.2 μm the maximum extent of the emission is ∼2″.0 (∼198 AU), which is about 90% the size of the 10 μm emission. Therefore, the same population of grains may emit most or all of the extended fluxes at both 10 and 18 μm.

In Figure 1 we present normalized scans through both HD 141569 and the point-spread function (PSF) star. The differences in the widths of the source and the PSF star are clearly evident. Quadratic deconvolution of the source with the PSF gives FWHM sizes of 34 AU at 10 μm and 62 AU at 18 μm for the extended emission near the star. Compared to the full extent of the mid-IR–emitting size of the disk (∼200 AU), the relatively small values of the dust FWHM sizes suggest that the mid-IR emission is sharply peaked close to the star, with much lower level extended emission farther out. Inspection of Figures 1*a* and 1*c* shows a noticeable difference in the source profile along the major axis at the two different wavelengths. While this difference can be attributed to a temperature gradient in the mid-IR–emitting dust, R. Sylvester (1999, private communication) has noted that it could also be related to different dust components dominating the emission in the two passbands. A mid-IR spectrum of HD 141569 by Sylvester et al. (1996) shows that there is strong emission in the 7.7 μm polycyclic aromatic hydrocarbon ("PAH") band and somewhat weaker emission in the 11.3 μm PAH band. Our broadband ($\Delta\lambda$ = 5.1 μm) flux measurement at 10.8 μm includes a contribution from this PAH emission. Below, we estimate what effect the presence of this PAH emission could have on our conclusions.

The overall size of the emission around HD 141569, a radial extent of 100 AU at both 10.8 and 18.2 μm, is comparable to the sizes of the mid-IR–emitting regions of both the archetype Vega-like source β Pic (A5 V) and the debris disk around HR 4796A (A0 V). Lagage & Pantin (1994) measured 10 μm emission from β Pic out to 100 AU from the central star. Recent

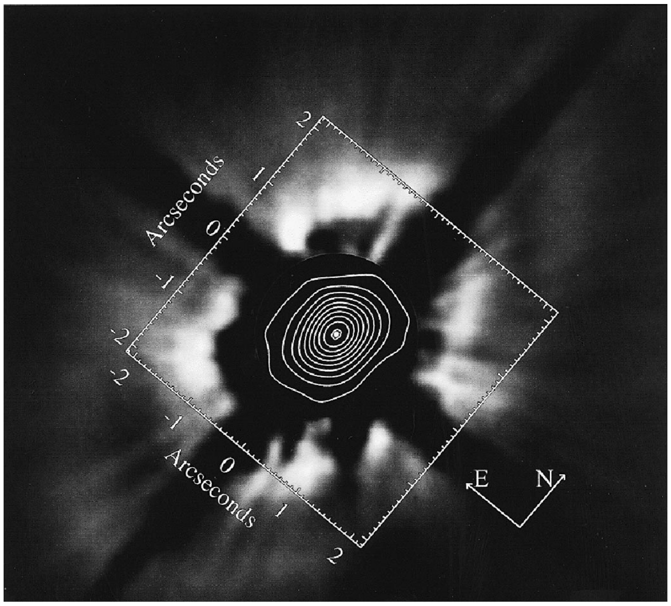

Fig. 2.—NICMOS image and OSCIR contours of HD 141569. 18.2 μm contours over a 1.1 μm image from Weinberger et al. (1999). Contours (in units of mJy arcsec^{-2}) are spaced linearly at 50, 113, 177, 241, 305, 369, 433, 497, 561, and 625. The lowest contour level is about 4 times the smoothed noise. The mid-IR contours were registered to the stellar position given on the near-IR image.

observations of the disk around HR 4796A show that it too emits both 10 and 18 μm radiation out to a distance of 95 AU (Telesco et al. 2000). Our estimates of the source size are consistent with similar mid-IR images of the source presented by Silverstone et al. (1999).

3.2. *Dust Temperature and Grain Size*

We can use our observations at two wavelengths to estimate the temperature and size of the grains responsible for the mid-IR emission. With assumptions about the composition of the grains and the dependence of the grain emission efficiency on wavelength, we can calculate a temperature of the dust. Since the emission efficiency of a dust particle depends on its size, a smaller grain in equilibrium with the radiation field will be hotter. The calculated temperature then provides a basis for estimating the size of the particles emitting the radiation.

We can estimate an upper limit on the size of the mid-IR–emitting grains by assuming that all of the 18.2 μm radiation comes from the same region around the star as the 10.8 μm flux. Quadratic subtraction of the PSF from the source at 10.8 μm gives an FWHM value of 34 AU. Since the emission at 10.8 μm at distances greater than this is at a very low level, we can say that a significant fraction of the 10.8 μm–emitting dust orbits within 20 AU of the star. This provides a lower limit on the dust temperature and therefore an upper limit on the grain size. To proceed further, we use a model developed by the University of Florida Dust Dynamics Group. This modeling technique was used to analyze similar data on the circumstellar disk around HR 4796A (Wyatt et al. 1999; Telesco et al. 2000). The model assumes that the grains are spherical Mie particles composed of astronomical silicates (Draine & Lee 1984) with density $\rho = 2.5$ g cm^{-3}.

The temperature of the dust particles determines the observed flux ratio, and we estimate the grain size by matching the observed flux ratio to the flux ratio calculated for grains of different diameters located at a distance of 20 AU from the star. The results of the model show that spherical Mie particles composed of astronomical silicates with a temperature ~170 K and a diameter of 2 μm fit the observed mid-IR flux ratio. More detailed models of HD 141569 produced by Sylvester & Skinner (1996) indicate a comparable value for the upper limit to the characteristic grain size.

Modeling of the disk of HR 4796A in Wyatt et al. (1999) and Telesco et al. (2000) shows that, with the assumption that they are spherical Mie particles, the mid-IR–emitting dust grains in that disk are also approximately 2 μm in size. Mid-IR aperture photometry and spectrophotometric observations of β Pic (Telesco et al. 1988; Telesco & Knacke 1991; Aitken et al. 1993) imply the presence of 1–3 μm grains in that disk. Van der Bliek, Prusti, & Waters (1994) reanalyzed the *IRAS* data on Vega and proposed that the dominant grains in that archetypal disk are on the order of 1–10 μm in size. The mid-IR spectrum of HD 141569 by Sylvester et al. (1996) shows that there is emission in the mid-IR PAH bands that contributes to our 10.8 μm flux estimate. To investigate how our deduced grain size estimates change due to this contamination, we ran the models assuming that none, 50%, and 75% of the 10.8 μm flux was emitted by PAH grains. Our grain size estimates ranged from 2 μm (no contamination) to 5 μm (75% contamination). Even with most of the flux coming from the PAH grains, the derived grain sizes estimates are consistent with those in other debris disks.

The fact that the HD 141569 may have dust of this size has important implications for our understanding of the evolution of the disk. By considering the ratio of the radiation force to the gravitational force on a particle (called β), we can investigate the effects of the stellar radiation on these particles. As summarized in Artymowicz (1988), $\beta \propto \langle Q_{\rm pr}\rangle\ (L_*/M_*)/R\rho$, where R is the particle radius, ρ is its density, $\langle Q_{\rm pr}\rangle$ is the radiation pressure efficiency averaged across the stellar spectral energy distribution, and L_*/M_* is the ratio of the stellar luminosity and mass. Using the stellar parameters for HD 141569 from van den Ancker et al. (1998) [$\log(L_*/L_\odot) = 1.35$; mass = 2.3 $M_\odot$], we have calculated β as a function of particle size for astronomical silicate Mie spheres with density ρ = 2.5 g cm^{-3}. For 2 μm diameter particles, we infer a value of $\beta \approx 3$. Particles with $\beta > 1$ are on unbound, hyperbolic orbits and will be removed from the system in a very short time. In the case of HD 141569, this is on the order of a few hundred to a thousand years, depending on where in the disk the high-β particles were formed. The models show that the value of β remains above unity for particles smaller than 5 μm in diameter. Consequently, we conclude that the mid-IR–emitting particles will be removed from the system very quickly even if our upper limit underestimates the grain size by a factor of 2 or more. Since the removal time of the grains from the disk is much less than the assumed age of the system (>10^7 yr), we conclude that the mid-lR–emitting grains are not primordial and have been replenished through some mechanism. One possible scenario for the replenishment of these particles is through collisions of larger bodies, as is apparently the case for β Pic (Artymowicz 1997) and HR 4796A (Wyatt et al. 1999; Telesco et al. 2000).

3.3. *Comparison with NICMOS Image*

Weinberger et al. (1999) made coronagraphic observations of HD 141569 at 1.1 μm with NICMOS. They used a 0$''$.6 diameter spot, but instrumental effects rendered data within 0$''$.9

of the central star unusable. Their images show what appears to be an almost face-on circumstellar disk. The near-IR flux, which is probably light from the star scattered by dust in the disk, extends out to a radius of ∼4″ (400 AU; Weinberger et al. 1999). The position angle of the major axis of the near-IR disk is equal to that of the mid-IR emission. The NICMOS image also shows evidence for a gap in the dust at a radius of ∼2.″5. As suggested by Weinberger et al. (1999), one way to form such a gap is by the gravitational influence of a planetary companion to the star.

Figure 2 shows the OSCIR 18.2 μm contours overlaid onto the 1.1 μm NICMOS image. The thermal emission arises much closer to the star than the near-IR flux. In fact, nearly all of the detected mid-IR emission comes from within the region blocked by the coronagraphic spot. Except for circumstances in which the transient heating of small grains can cause abnormally high temperatures far away from a heating source, we expect grains farther away from a source to be cooler. In § 3.2 we estimated that the mid-IR–emitting grains have a characteristic temperature of ∼170 K. We therefore expect the grains seen in the near-IR image to be cooler than that. In their compilation of Vega-like sources, Walker & Wolstencroft (1988) fit a 95 K blackbody to the far-IR (25 and 60 μm) *IRAS* fluxes for this source. However, the 12 μm *IRAS* point was conspicuously high compared to the otherwise good fit. This implies that there may be a second population of dust at a temperature higher than 95 K that is responsible for the 12 μm excess in the source. The mid-IR contours in Figure 2 probably indicate the location of those warmer grains.

The OSCIR and NICMOS data shown in Figure 2 may be direct observational evidence for two separate populations of dust grains: the inner, warmer grains that emit the mid-IR (10 and 18 μm) radiation and the more distant grains that are responsible for the scattered near-IR flux seen in the NICMOS image and the far-IR (60 and 100 μm) emission detected by *IRAS*. The strong PAH emission seen in the spectrum of this source (Sylvester et al. 1996) indicate that this proposed "inner population" cannot simply be warm silicates. The PAH grains in the innermost regions of the disk may indeed be mixed with silicates, for which there is not yet direct evidence. Even if the mid-IR–emitting grains were blackbodies, they would contribute a very tiny fraction of the 60 and 100 μm excess (41 and 7 mJy, respectively), and, therefore, the longer wavelength excess must come from other grains. This situation is similar to that for β Pic in which the mid-IR emission comes from a relatively small inner region of the total disk. Images in the visible and near-IR by Burrows & Krist (1995), Kalas & Jewitt (1995), and Smith & Terrile (1984) show that the disk around β Pic extends out to at least a radius of 10″ (∼200 AU) from the star in the near-IR and much farther than that in the visible.

4. CONCLUSIONS

Our conclusions are as follows.

1. Our mid-IR images made with OSCIR on Keck show extended emission around the B9.5 Vega-like star HD 141569 at 10.8 and 18.2 μm. The emission is detected out to a radius of ∼1″ (100 AU) at both wavelengths. Since the emitting regions at both wavelengths are of comparable size, the same population of dust may emit both the 10.8 and 18.2 μm radiation. The size of the mid-IR–emitting region of this system is comparable to those of HR 4796A and the archetype Vega-like source β Pic.
2. We use the 10.8 and 18.2 μm images to place a lower limit of 170 K on the temperature and an upper limit of 2 μm on the diameter of the dust grains responsible for the mid-IR emission if they are Mie spheres composed of astronomical silicates.
3. The value of β, the ratio of the radiation force to the gravitational force on a particle, for these particles is ∼3. Particles with a value of $\beta > 1$ are on unbound, hyperbolic orbits and will be removed from the system on a very short timescale. In the case of HD 141569, the removal takes place in a few hundred years. We therefore conclude that, if they are silicate Mie spheres, the grains responsible for the mid-IR emission are not primordial. They have been replenished by some mechanism, perhaps through collisions of larger bodies, as is also apparently the case for HR 4796A.

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