

ADAPTIVE OPTICS NULLING INTERFEROMETRIC CONSTRAINTS ON THE MID-INFRARED EXOZODIACAL DUST EMISSION AROUND VEGA¹

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ABSTRACT

We present the results of mid-infrared nulling interferometric observations of the main-sequence star α Lyr (Vega) using the 6.5 m MMT with its adaptive secondary mirror. From the observations at 10.6 μm , we find that there is no resolved emission from the circumstellar environment (at separations greater than 0.8 AU) above 2.1% (3σ limit) of the level of the stellar photospheric emission. Thus, we are able to place an upper limit on the density of dust in the inner system of 650 times that of our own solar system's zodiacal cloud. This limit is roughly 2.8 times better than those determined with photometric excess observations such as those by *IRAS*. Comparison with far-infrared observations by *IRAS* shows that the density of warm dust in the inner system (<30 AU) is significantly lower than cold dust at larger separations. We consider two scenarios for grain removal, the sublimation of ice grains and the presence of a planetary mass "sweeper." We find that if sublimation of ice grains is the only removal process, a large fraction ($>80\%$) of the material in the outer system is ice.

Subject headings: circumstellar matter — instrumentation: adaptive optics — stars: individual (Vega) — techniques: interferometric

1. INTRODUCTION

Circumstellar material around main-sequence stars was first discovered in 1983 by the *Infrared Astronomical Satellite* (*IRAS*), when observations of α Lyr (Vega) showed far-infrared (FIR) emission in excess of that expected from the stellar photosphere (Aumann et al. 1984). These detections were made at 60 and 100 μm and were followed by similar discoveries around other stars, including β Pic and α PsA (Gillett 1986). Since then, many stars have been found to have excess FIR emission, and this emission has been thought to be associated with thermal emission from cold circumstellar debris, similar in nature to the Kuiper disk surrounding our solar system.

Although several cases of this so-called Vega phenomenon have been confirmed at FIR wavelengths, to date there have been no resolved detections of mid-infrared (MIR) emission surrounding main-sequence stars older than a few tens of megayears. Such a detection would be indicative of warm ("room temperature") dust close to the star, analogous to the zodiacal dust in our own solar system. Any material emitting at 10 μm would be in the "habitable zone" of a system in which liquid water could exist. The presence of dust would also necessitate the presence of planetesimals that would, through collisions, regenerate the dust that is normally depleted on fast timescales because of Poynting-Robertson drag and/or radiation pressure blowout. Resolved MIR disks have been detected around the main-sequence A-type stars β Pic (Pantin et al. 1997; Weinberger et al. 2003) and HR 4796A (Jayawardhana et al. 1998; Jura et al. 1998), although HR 4796A is thought to be very young, with an age less than 10 Myr, and β Pic is estimated to be less than

30 Myr old (Barrado y Navascués et al. 1999). Detection of a MIR disk around an older star like Vega (350 Myr old; Lachaume et al. 1999) proves to be more difficult since stars of this age are thought to have shed their natal circumstellar disks. Any new dust generated in the manner described above would have a total flux several orders of magnitude below that of the host star.

In order to mitigate the difficulty of observing such a faint source in the presence of a bright star, our observations of Vega make use of nulling interferometry and the adaptive secondary mirror for the MMT. Nulling interferometry is a relatively new technique to detect resolved faint structure in the presence of a much brighter unresolved point source. The Bracewell Infrared Nulling Cryostat (BLINC) uses two parts of the MMT's 6.5 m primary mirror to create an interferometer with two elliptical 4.8 \times 2.5 m subapertures and a baseline of 4 m. These two subapertures are overlapped in the pupil plane with an appropriate path difference between the beams to destructively interfere the central point source in the image plane. The effect of this optical arrangement is to create a sinusoidal transmission pattern for the object on the sky, with destructive interference on the point source (star). Light from half an interference fringe width away constructively interferes, enhancing the flux. Thus, the technique can detect material as close to the star as one-quarter of the fringe spacing where the light is neither suppressed nor enhanced. This corresponds to 0".12 for the configuration used on the MMT (for Vega, this is a projected separation of less than 1 AU). Nulling interferometry is unique in that it can be used to determine the relative contributions of the star and circumstellar material to the total flux, independent of models of the stellar photosphere and nearby environment. Full details of the BLINC instrument and its implementation can be found in Hinz (2001). The MMT's adaptive secondary mirror provides correction of atmospheric wave-front aberrations in the incoming light, allowing destructive interference to be precisely tuned for the deepest possible suppression of starlight.

In this Letter, we present results from 10.6 μm nulling interferometric observations of the main-sequence star α Lyr (Vega) that are part of a larger systematic survey of solar neigh-

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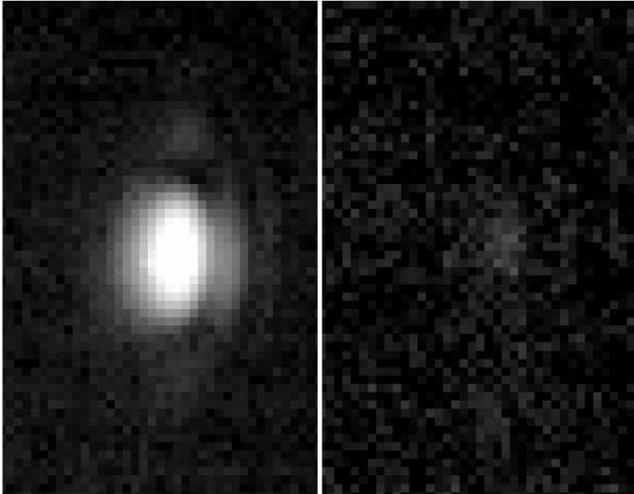


FIG. 1.—Constructively and destructively interfered images of α Lyr. The instrumental null is $3\% \pm 1\%$. The elliptical shape of the star is due to the elliptical shape of the subapertures in the interferometer. The additional structure seen in the constructive image (*above and to the right of the central image*) are part of the star’s Airy pattern.

borhood main-sequence stars. We discuss constraints of the distribution, density, and composition of the dust in the Vega system and compare our results with previously published observations of Vega at different wavelengths.

2. OBSERVATIONS AND DATA REDUCTION

Observations were made in 2003 May at the MMT 6.5 m telescope on Mount Hopkins, Arizona. The observations made use of the world’s first adaptive optics (AO) secondary mirror. Since the deformable mirror is the telescope’s secondary mirror, there is no need for an intermediate set of reimaging and correcting optics as in traditional AO systems. Thus, the light from the secondary is fed directly into the science camera, optimizing throughput and decreasing the background emissivity in the MIR by avoiding the use of extra warm optics. Wave-front sensing is accomplished in a separate assembly using visible light diverted from the telescope beam. The wave-front sensor is a Shack-Hartmann sensor with a EEV CCD39a detector, operating at a frame rate of 550 Hz. For further details regarding the MMT AO system, we refer the reader to Wildi et al. (2003) and references therein.

The main advantage in using AO with nulling interferometry is the stabilization of the wave front of light, allowing us to precisely adjust the path difference between the two beams of the interferometer and thus obtain the deepest possible null. However, in the case of these observations, the suppression of starlight was limited during the run by a slight mechanical vibration (measured during subsequent observations to be about 20 mas at a frequency of 20 Hz) in the telescope, which caused a wave-front aberration and therefore a slight phase error between the two beams of the interferometer. This caused the instrumental nulls to vary slightly and limited the suppression to the levels described below (about 3% residual light), where theoretically a deeper null (several tenths of a percent) would be possible.

Nulling observations were taken with a broadband N filter (8.1–13.1 μm). For the science object, Vega, seven sets of 20 frames were taken with the star destructively interfered, for a total of 140 frames, each frame with an integration time of

TABLE 1
SUMMARY OF OBSERVATIONS OF VEGA^a

Set	Position Angle (deg)	Instrumental Null (%)
1	72	2.7
2	73	2.9
3	53	4.4
4	36	4.5
5	17	3.9
6	−21	4.0
7	−22	3.6

^a See § 2 for explanation.

3 s. Observations of Vega in constructive interference were taken between the destructive sets, with the same integration times (Fig. 1). All frames were sky-subtracted using off-source frames taken in between each set of observations of Vega. The “instrumental null” for each destructively interfered image to the flux of the constructively interfered image (i.e., instrumental null = nulled flux/full flux), expressed as a percent. Each destructively interfered set of frames was examined for the frame with the best instrumental null. In order to calibrate these values, observations of two point-source (unresolved) standard stars, α Her and γ Dra, were taken before and after the observations of Vega.

The best instrumental nulls for the seven destructively interfered sets of images are shown in Table 1. Each set of frames was taken at a different orientation of the interferometer baseline relative to the sky, which allows us to probe for evidence of an inclined disk structure, if resolved emission is detected (see Liu et al. 2003 for an explanation of this technique). The standard deviation in the derived null for the sets of frames is 0.7%, resulting in an average value of the null of $3.7\% \pm 0.7\%$. The nulls for the individual point-source calibrators were $3.6\% \pm 0.5\%$ from three sets of observations of α Her and $3.4\% \pm 0.4\%$ from seven sets of observations of γ Dra. This results in a combined average null on the point-source standard stars of $3.5\% \pm 0.4\%$. “Source nulls” were calculated for Vega by subtracting the null obtained for the standard stars from the instrumental null achieved for Vega (i.e., source null = instrumental null − standard null). This value represents the flux of resolved emission around a star, as a percentage of the full flux of the star when constructively interfered. A nonzero source null means that resolved emission has been detected.

3. RESULTS AND DISCUSSION

The source null derived for Vega is $0.2\% \pm 0.7\%$ (1σ error), consistent with zero, which indicates that we are not detecting resolved emission at our current levels of sensitivity and spatial resolution.⁶ This allows us to place constraints on the distribution and amount of exozodiacal dust surrounding Vega. We are confident (3σ) that there is no resolved emission at 10.6 μm around Vega above the 2.1% level (0.9 Jy) outside of 0.8 AU from the star. In order to compare this limit with the zodiacal dust density in our own solar system, we use the zodiacal dust model of Kelsall et al. (1998). The Kelsall et al. model would result in a nulled flux of 1.4 mJy (or 0.0033% of Vega’s flux) if placed at the distance of Vega. Scaling up this solar model to our 3σ limit for Vega corresponds to a dust density limit of about 650 times our solar system’s zodiacal

⁶ In contrast, for an example of a positive detection of circumstellar material, see Liu et al. (2003).

dust. Additionally, we find that the null does not vary significantly with observations at different rotations of the interferometer baseline (over a range of about 90°), indicating that there is no evidence of an inclined disklike structure.

A further analysis can be made by comparing the observed limits to an estimate of the expected flux of our own zodiacal dust at the age of Vega (350 Myr). For a collisionally replenished disk with a dust-removal timescale much shorter than the lifetime of the system, we expect $f_d \sim t^{-2}$, where f_d is the dust flux as a fraction of stellar flux (Spangler et al. 2001). Using this relation, we find that the transmitted signal from our zodiacal dust at the age of Vega (350 Myr) would be ≈ 270 mJy. Our limit of 0.9 Jy results in a limit on warm dust in the Vega system of about 3 times our own zodiacal dust, after accounting for dust evolution.

Previous studies of Vega in the FIR have found a significant amount of cold (50–125 K) debris in the system at large separations (several tens of AU and greater; Backman & Paresce 1993). From Poynting-Robertson drag, one would expect that this material would migrate inward and populate inner regions with material as well, which could be detected at MIR wavelengths. If one assumes that the excess flux at $25 \mu\text{m}$ (1.08 Jy; Backman & Paresce 1993) is due to thermal emission from cold debris, takes the temperature of grains as a function of distance from the star as $T \sim r^{-0.5}$ (Backman & Paresce 1993), and makes the conservative assumption that the optical depth profile of the circumstellar material is constant with radius,⁷ one would expect a flux of 11 Jy from blackbody grains at $10 \mu\text{m}$. This flux is calculated assuming thermal blackbody emission from the grains by integrating the product of the Planck function and optical depth over the spatial extent of the zodiacal dust.⁸ When this signal is observed through the transmission pattern of the interferometer, we estimate the final signal to be over 5 Jy. Using the $60 \mu\text{m}$ excess (7.75 Jy; Backman & Paresce 1993), with the same assumptions as above, the calculation yields an even greater detected excess of 470 Jy at $10 \mu\text{m}$. These expected $10 \mu\text{m}$ fluxes would have been easily detectable with our observations. However, we do not find this large excess, which indicates that the inner region of the Vega system is relatively clear of material compared to the outer region. This result is consistent with previous conclusions (Lagrange et al. 2000; Backman & Paresce 1993), although our observations are able to better constrain the upper limit of dust density in the Vega system by a factor of ≈ 2.8 times compared to *IRAS* observations, which provided an upper limit for warm dust density of 1800 times our solar system (Hinze 2001; Aumann et al. 1984).

The lack of substantial $10 \mu\text{m}$ emission surrounding Vega can be physically interpreted in different ways. One may draw a comparison to the HR 4796A system that was observed by Jura et al. (1998) to have a similar lack of warm material in the inner system. For the case of HR 4796A, they suggest two possible scenarios for the lack of warm dust in that system: the existence of a companion clearing out material or the destruction of ice particles by stellar radiation. Here we consider

the same explanations for the absence of material in the inner Vega system. For the latter scenario, we would expect water ice to sublimate at temperatures above 110 K (Pollack et al. 1994), and in fact we may already see evidence of this effect in the $25 \mu\text{m}$ emission that probes temperatures near the sublimation temperature and shows a smaller than expected excess compared to longer wavelengths. If the lack of material in the inner system is due to sublimation of ice grains, we can constrain the composition of the outer debris disk. To estimate this effect, we make the simplifying assumption that each grain is composed of either icy material that sublimates at 110 K, and thus is totally destroyed inward of about 45 AU, or silicates/metals grains that remain unaffected. Comparing our derived upper limit on dust flux at $10 \mu\text{m}$ (0.9 Jy) and the expected $10 \mu\text{m}$ flux using the $60 \mu\text{m}$ excess calculated above (470 Jy), and assuming that the density decrease in the inner system is due only to the sublimation of ice grains, this would require that the outer disk is comprised of 99.8% icy material, assuming optically thin material. Using the $25 \mu\text{m}$ excess to estimate the density contrast compared to the inner system, we find that the composition must be about 80% water ice, again if ice sublimation is the only cause of grain removal. For comparison, the large Kuiper Belt objects Pluto and Charon have densities of roughly 2 g cm^{-3} (Luu & Jewitt 2002), indicating higher fractions of silicate material in our own outer solar system than that of Vega, as determined by this study. This either suggests a significant difference in composition or points to another explanation for removal of the cold dust as it spirals in.

Another explanation for the lack of dust in the inner system is the presence of a sweeper companion. Previous observations in the millimeter and submillimeter (Wilner et al. 2002; Koerner et al. 2001; Holland et al. 1998) have detected dust in the Vega system at separations between $8''$ and $14''$ from the star (projected separations of 60–110 AU). The morphology of the dust is suggested to be the result of a planetary perturber. For example, Wilner et al. (2002) suggest a planetary companion of $3M_{\text{Jup}}$ at a separation of about 50 AU. It is conceivable that such a companion could be responsible for the contrast in density of circumstellar material between the outer and inner system found in this and previous studies. However, if one assumes that the temperature of grains follows the relation $T_g \sim r^{-0.5}$ (Backman & Paresce 1993, eq. [3]), the drop-off in mid-infrared excess between the $25 \mu\text{m}$ *IRAS* detection and the $10 \mu\text{m}$ observations in this study indicate a significant density decrease between 10 and 40 AU, suggesting that a planetary companion may be located at a closer separation than suggested by the millimeter observations. Recent near-infrared AO observations of Vega by Keck (Macintosh et al. 2003) and the Palomar 5 m telescope (Metchev et al. 2003) have attempted to detect planetary mass companions. These studies found no evidence of a massive (in excess of several Jupiter masses) planetary companion. However, the studies note that they do not probe masses for companions as low as those suggested by the millimeter observations.

Finally, we compare our results to those of Ciardi et al. (2001), who find near-infrared emission consistent with a circumstellar debris disk within 4 AU emitting at 3%–6% of the stellar flux. If we take this to be the case, and assume that the optical depth of material drops off as $r^{-0.4}$ (Backman et al. 1997) out to the $10 \mu\text{m}$ emitting region, we would expect a signal in the range of 1.5–3 Jy at $10 \mu\text{m}$, which would have been detected by our observations. We do not find this to be the case, which suggests that if a near-infrared disk is present, there is a steeper drop-off in the optical depth of dust than the $r^{-0.4}$ assumed here.

⁷ For reference, the solar system's radial optical depth profile is $\sim r^{-0.4}$ in the inner system ($r < 30$ AU) and $\sim r^{-4}$ for $30 \text{ AU} < r < 100$ AU (Backman et al. 1997). For our analyses, we assume that the grains are large enough to be considered blackbodies.

⁸ We set the inner radius of the disk at the dust sublimation radius of 0.25 AU, corresponding to a temperature of 1500 K, and the outer radius of the disk to the distance at which we expect the thermal emission at a given wavelength to peak given the T vs. r relation in Backman & Paresce (1993). The dust is assumed to be optically thin.

4. FUTURE DIRECTIONS

We are currently in the process of refining the nulling technology in order to achieve better suppression of starlight. Technical improvements include the addition of an internal servo loop in BLINC, which will actively monitor and correct the phase difference between the two beams of the interferometer in order to maintain the deepest possible null. Stabilizing the phase error will allow us to suppress the starlight by a factor of ~ 1000 . Scientifically, this improvement in the suppression will allow us to detect levels of zodiacal emission many times fainter than currently possible, in the 50–100 zody level. Using the refined nulling observations, we plan a survey of nearby main-sequence A-type stars to search for evidence of exozodiacal dust. These observations also lay the groundwork for a planned survey with the Large Binocular Telescope Interfer-

ometer, which will carry out nulling searches for exozodiacal dust at sensitivities approaching solar level.

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