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RESOLVED MID-INFRARED EMISSION AROUND AB AURIGAE AND V892 TAURI WITH ADAPTIVE OPTICS NULLING INTERFEROMETRIC OBSERVATIONS[1]

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ABSTRACT

We present the results of adaptive optics nulling interferometric observations of two Herbig Ae stars, AB Aur and V892 Tau. Our observations at 10.3 μm show resolved circumstellar emission from both sources. Further analysis of the AB Aur emission suggests that there is an inclined disk surrounding the star. The diameter of the disk is derived to be 24–30 AU with an inclination of 45°–65° from face-on and a major-axis position angle of 30° ± 15° (east of north). Differences in the physical characteristics between the mid-IR emission and emission at other wavelengths (near-IR and millimeter), found in previous studies, suggest a complex structure for AB Aur's circumstellar environment, which may not be explained by a disk alone. The similarity in the observed size of AB Aur's resolved emission and that of another Herbig Ae star, HD 100546, is likely coincidental, as their respective evolutionary states and spectral energy distributions suggest significantly different circumstellar environments.

Subject headings: circumstellar matter — instrumentation: adaptive optics — stars: individual (AB Aurigae, V892 Tauri) — stars: pre–main-sequence — techniques: interferometric

1. INTRODUCTION

Over the past several years, numerous circumstellar disks have been observed surrounding pre–main-sequence (PMS) stars, including Herbig Ae (HAE) stars. HAE stars, the evolutionary precursors to intermediate-mass main-sequence stars like Vega, show infrared (IR) emission in excess of what is expected from their photosphere. This emission was thought to originate from optically thick, geometrically thin circumstellar disks (Hillenbrand et al. 1992; Lada & Adams 1992), a model later modified to include disk flaring in order to explain features in the observed spectral energy distributions (SEDs) of the disks (Kenyon & Hartmann 1987; Chiang & Goldreich 1997). Alternative models also include dusty envelopes of material or a combination of a disk and an envelope (Hartmann et al. 1993; Miroshnichenko et al. 1999). Given the variety of models used to explain the IR excess around PMS stars, observations of their circumstellar environments are necessary to determine which of these models is most representative of their true environment.

The HAE star AB Aurigae (A0; $d = 144$ pc; van den Ancker et al. 1998) has been the subject of many studies based on observations at several different wavelengths. The star has an estimated age of 2–5 Myr (Mannings & Sargent 1997; van den Ancker et al. 1998). Near-IR (NIR) emission from the AB Aur circumstellar region has been observed, probing thermal emission in the inner AU of the disk using long-baseline interferometry (Eisner et al. 2003; Millan-Gabet et al. 2001). Both studies suggest the presence of a slightly inclined distribution of dust with an empty or optically thin inner region (i.e., a ringlike structure). Another recent study in the NIR has detected scattered light from the disk at greater separations (out to 580 AU) and finds the disk to have a small inclination (Fukagawa et al. 2004). Observations in the mid-IR (MIR) suggest evidence for resolved circumstellar material at 12 and 18 μm at several tens of AU from the star (Chen & Jura 2003; Marsh et al. 1995). Longer wavelength observations of AB Aur in the millimeter were shown to have spatially resolved molecular line emission at a few hundred AU (Mannings & Sargent 1997). Reflection nebulosity has also been detected in the optical by Grady et al. (1999), who finds material out to 1300 AU and a disk inclination of less than 45°.

V892 Tau is an HAE star located in the Taurus-Auriga star-forming region, at a distance of about 140 pc (Elias 1978). NIR speckle interferometry of the star revealed an elongated structure with a position angle (P.A.) of 90°. The source of emission is speculated to be either a highly inclined disk or a bipolar outflow (Haas et al. 1997).

In this Letter, we present results of nulling interferometric observations in the MIR of these two HAE stars, AB Aur and V892 Tau, in which we have clearly resolved emission from both sources. From these observations, we infer and discuss the physical properties of the circumstellar material in the AB Aur system.

2. OBSERVATIONS AND DATA REDUCTION

Observations were made in 2002 November and 2004 February at the 6.5 m MMT Observatory on Mount Hopkins, Arizona. The BracewelL Infrared Nulling Cryostat (BLINC; Hinz 2001) provided suppression of starlight, and the Mid-Infrared Array Camera (MIRAC; Hoffmann et al. 1998) provided the final stop for the two beams of the interferometer. The 2002 run consisted of preliminary observations of both science targets at 10.3 μm (10% bandpass). Four sets of 500 frames (each frame with 0.5 s integration) were taken for each target, resulting in 2000 frames for each source. Images of a point-source calibrator, α Ari, were taken before and after the science observations. Frames were sky-subtracted using off-source fields taken in between each set of frames. Photometry was extracted from each of the science frames, and each set of frames was examined for

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TABLE 1
Source Nulls for AB Aur

Set Number	Rotation (deg)	Major-Axis Position (deg east of north)	Calibration 1 (%)	Calibration 2 (%)	Calibration 3 (%)
1	−160	4	26.5	18.9	16.9
2	−135	170	20.7	19.1	11.1
3	−105	131	14.9	8.1	5.3
4	−75	107	13.1	9.7	3.5
5	−45	77	18.9	12.7	9.3

the best instrumental null (instrumental null = nulled flux/constructive flux). Source nulls were derived for each set of frames (source null = instrumental null − calibrator null; see Liu et al. 2004 for a full description of nulling calibration and diagnostics as well as a typical image from the BLINC-MIRAC camera).

Follow-up observations were made in 2004 at the MMT, also at 10.3 μm, utilizing BLINC-MIRAC with the telescope's 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 between the secondary mirror and science camera. This has the benefit of optimizing throughput and decreasing background emissivity in the MIR by avoiding the use of extra warm optics. The adaptive secondary also provides two major benefits particular to our nulling observations: (1) The wave front is stabilized, allowing us to precisely tune the interferometer for the best possible suppression of starlight. (2) Fewer data frames need to be taken since the wave front stabilization allows us to precisely tune the destructive interference. These observations included 15 sets of 10 frames (150 frames total) for AB Aur in destructive interference and three sets of 10 frames for V892 Tau in destructive interference. Frames of the objects in constructive interference as well as off-source sky frames were taken in between each set of nulled images.

In order to probe the spatial distribution and orientation of the circumstellar emission, the follow-up observations of AB Aur were taken at several different rotations of the interferometer baseline relative to the sky (see Liu et al. 2003 for a full description of this technique). This was also attempted for V892 Tau; however, poor observing conditions on the night this object was observed allowed only limited follow-up.

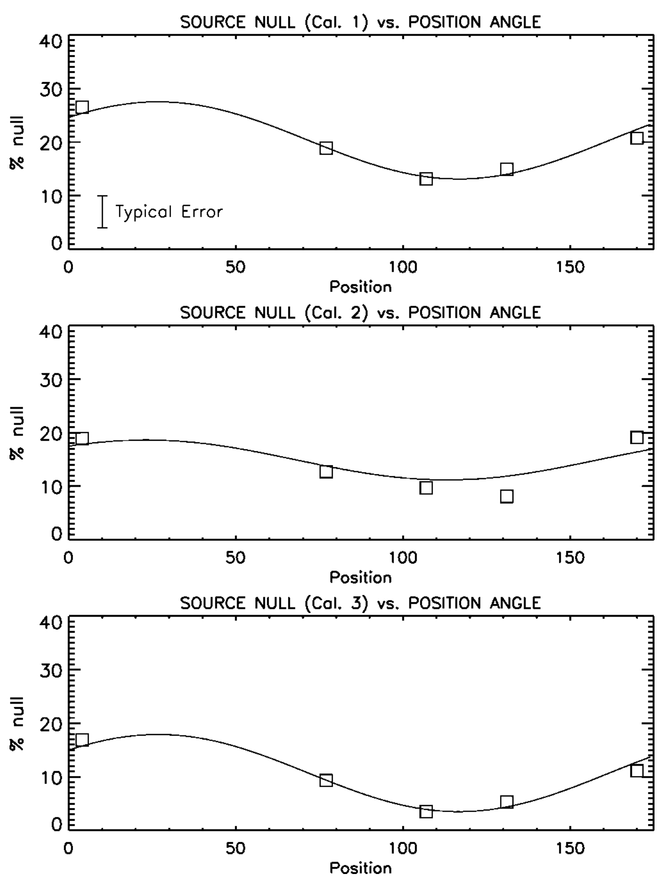

Fig. 1.—Source nulls vs. rotation of interferometer baseline derived for AB Aur for each of three calibrations described in the text. The variation in null is consistent with the presence of an inclined disk.

3. RESULTS AND DISCUSSION

The preliminary observations in 2002 show evidence for resolved emission in both sources. Source nulls derived from these non-AO observations show the resolved flux surrounding each object to be at a level of 10%–20% of its full 10.3 μm flux (3–6 Jy for both sources). Follow-up observations in 2004 are described below.

3.1. *V892 Tau*

Because of the limited observations of V892 Tau in 2004, we make no conclusions about the spatial distribution of emission around this object. However, from our observations, we are able to confirm the presence of extended emission in the MIR first uncovered by our preliminary observations. The extended emission is verified to be at a level of 11% ± 6% (about 3 Jy; 2 σ error) of the full 10.3 μm flux of the star. The resolved emission is detected at a P.A. of 164° and, assuming a Gaussian flux distribution is responsible or the emission, has a diameter of about 20 AU. Follow-up observations are needed to probe the geometry of the resolved emission.

3.2. *AB Aur*

Observations of AB Aur in 2004 were taken at five different rotations of the interferometer baseline spanning 115° in increments of 30°. This rotation allows us to probe a range of P.A.'s around the star for resolved emission. The source null for each rotation and corresponding P.A. is listed in Table 1 for each of three different calibrations of the data (see next paragraph). Plots of the data are shown in Figure 1. If the emitting dust is in an inclined disk, one would expect the dependence of the source null versus P.A. to be sinusoidal.[4] From a fit to the data, of the form $N = a + [b \sin(\mathrm{P.A.} + \theta)]$, with the period fixed at 180° (Liu et al. 2003), we derive physical properties for an inclined disk around AB Aur. For

[4] The transmitted signature of the nulling interferometer is an interference pattern with interference fringes along the baseline. If these fringes are parallel to the major axis of a disk, more of the disk's light will be nulled, resulting in a lower percentage of remaining light. When the fringes are aligned orthogonally to the major axis, the value of the source null will be higher (i.e., there is more light remaining). Therefore, there should be a sinusoidal variation in null with respect to the rotation of the baseline.

the fit, the values of a, b, and θ are physically related to the size, inclination, and P.A. of the major axis, respectively.

Observations of the calibrator star, β Gem, were taken before and after the observations of AB Aur. The calibrator shows a significant change in the level of null we were able to achieve during the observations, due probably to changes in observing conditions and the effectiveness of AO wave front correction. As a result, we calibrate our data (calculate the source nulls) for AB Aur in three different ways to determine how this affects the results. The different calibrations are as follows: (1) We use the first calibrator measurement to calculate all the source nulls. (2) We use a linear fit (in time) between the two calibrator measurements to calculate the source nulls. (3) We use the last calibration to calculate all the source nulls.

All three methods of calibration yield a result in which the dust distribution is significantly more resolved in one P.A. (≈30°) than another offset by 90° (≈120°). This result is suggestive of a flattened or elongated structure as the source of MIR excess emission. If we assume two simple brightness distributions (a Gaussian disk and a ring), physical parameters are derived from the fits to the source null versus P.A. (Table 2). For each model, we have derived the size and inclination of the material needed to reproduce the null versus P.A. profile we have observed. This is repeated for each of the three calibrations, allowing us to assess the error introduced by the calibration issues described above. All three calibrations yield similar results and indicate that the 10.3 μm emission originates from a separation 12–17 AU from the star. The presumed disk has a significant inclination, 45°–65° from face-on, and the P.A. of the major axis of the disk is 30° ± 15°. If the actual distribution of warm dust is a combination of a flattened structure and a uniform symmetric component (such as a disk plus envelope), then the disk component would need to be more inclined to account for the amplitude in null variation.

Previous studies have also observed AB Aur at MIR wavelengths. Chen & Jura (2003) used the Keck I telescope to observe the star at 11.7 and 18.7 μm. They find that it is marginally resolved at the longer wavelength. At 18.7 μm, they find an angular diameter of about 1″ at the half-maximum flux level. This suggests that the 18 μm emission is originating from a separation of about 70 AU, several times greater than the 10 μm emission. A study by Marsh et al. (1995) finds evidence for resolved emission at 11.7 and 17.9 μm and derives diameters of 40 and 80 AU for the emission, respectively. Taking into account the derived size scales from this and both previous MIR studies (separations of 12–17, 20, and 40–70 AU for the 10.3, 11.7, and 18 μm emission, respectively), we note that the wavelength versus separation profile agrees with the radial temperature profile expected for a flared disk, $T \sim r^{-1/2}$ (Chiang & Goldreich 1997), assuming that the emission is primarily thermal in nature. We also note that the NIR study of (Millan-Gabet et al. 2001) finds that the thermal 2 μm disk size is about 0.7 AU, which is also roughly consistent with a continuous flared disk.

Studies at other wavelengths include NIR studies (e.g., Fukagawa et al. 2004; Eisner et al. 2003) and millimeter observations (Natta et al. 2001; Mannings & Sargent 1997); Mannings & Sargent (1997) found that AB Aur is "marginally resolved" in molecular line emission at 3 mm. They find a major-axis P.A. of 79° with an inclination of 76° from face-on. The significant inclination of the disk agrees with the derived inclination of this study. However, more recent studies in the millimeter (Natta et al. 2001 and references therein) cite a much smaller inclination (<30°). A recent NIR study by Fukagawa et al. (2004) using AO coronagraphic observations finds a scattered light disk in the H band with a P.A. of 58°

TABLE 2

Derived Parameters for the AB Aur Disk

Calibration Set	Gaussian FWHM (AU)	Inclination (deg)	Ring Diameter (AU)	Inclination (deg)
1	30 ± 3	47 ± 5	34 ± 3	45 ± 5
2	27 ± 3	52 ± 5	30 ± 3	50 ± 5
3	24 ± 2	64 ± 6	28 ± 3	63 ± 6

and a significantly smaller inclination of 30° from face-on. Eisner et al. (2003) used the Palomar Testbed Interferometer to obtain K-band observations of the inner (<0.5 AU) disk surrounding AB Aur and find the inclination to be small, within 30° of face-on, in agreement with Fukagawa et al. (2004). The observations of this study suggest a greater inclination for the MIR emission. One also notes that the major-axis P.A. derived for the MIR emission in this study differs significantly (50°–70°) from previous studies both in the NIR and millimeter. This points to a difference in geometry for the dust between the inner (a few AU) and outer (hundreds of AU) system. The biggest difference between this study and those at other wavelengths is in the inclination of the disk. Previous studies at several different wavelengths all agree on a significantly smaller inclination than found by this study. This, in combination with the discrepancies in the P.A. of the disk, suggests that the structure may be more complex than a disk alone, where emission at different wavelengths is dominated by material with a different distribution.

Comparing AB Aur to a sample of 14 HAE stars observed in the MIR by Leinert et al. (2004) may be helpful in placing AB Aur into context and gaining insight into their circumstellar environments. The Leinert et al. (2004) study finds a correlation between the size of resolved emission and the SED classifications of Meeus et al. (2001). They find that the Meeus et al. type I sources, characterized by a rising MIR SED, tend to have spatially larger circumstellar emission regions. By contrast, type II sources have flat or declining MIR SEDs and have smaller resolved sizes. The resolved size of the AB Aur emission found in this study would classify AB Aur as a type I source, consistent with the initial classification by Meeus et al. (2001) by the SED alone. While it appears that the each type shows similar physical characteristics, there also seems to be evidence that a simple, all encompassing physical model may not be an ideal explanation for each Herbig type. For example, it is interesting to note some differences, from nulling observations and other previous studies, between AB Aur and another resolved type I HAE star, HD 100546. The primary difference highlighted by nulling observations is that AB Aur's radial wavelength (temperature) profile seems to be consistent with a continuous disk, whereas HD 100546's relative 10 μm versus 20 μm emission region sizes suggest an inner clearing (Liu et al. 2003). Other studies have found differences in the age (10 Myr for HD 100546 vs. 2–5 Myr for AB Aur: van den Ancker et al. 1998; Mannings & Sargent 1997) and evolutionary states (Bouwman et al. 2003) of the two stars. It seems, therefore, that although the two stars show similarities in the size of their resolved emission at 10 μm, the emission arises from physically different distributions of circumstellar dust.

4. ONGOING WORK: SURVEYS OF INTERMEDIATE-MASS STARS

The observations of AB Aur and V892 Tau presented here are part of a survey of 14 nearby HAE stars for resolved circumstellar material in the MIR. Nulling interferometric observations with the BLINC-MIRAC instrument from the MMT and

Magellan I (Baade) 6.5 m telescopes are now complete. Results and an analysis of the full sample will be presented in an upcoming paper. Also currently underway is a survey of nearby intermediate-mass main-sequence stars for second-generation exozodiacal dust, again utilizing nulling interferometry with AO. Completed observations include those of Vega, presented in Liu et al. (2004).

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