Detection of a gap in a circumstellar disk, from high-resolution mid-infrared observations

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Abstract

The Herbig Ae star, AB Aur, was observed at 11.7 μm wavelength using the Cornell SpectroCam-10 imaging spectrometer on the 5-m Hale Telescope. The observed images were deconvolved using a Bayesian estimator which provides superresolution from the incorporation of prior information (the positivity of intensity and the finite support of the emission), yielding a final spatial resolution of 0."17, corresponding to 27 AU at a distance of 160 pc. Our deconvolved images have resolved the circumstellar disk (diameter $\sim$50 AU), and revealed the presence of a central depression whose size ($\sim$30 40 AU) is consistent with the outer diameter of the gap which had been inferred independently using a model-fit to the object's spectral energy distribution. We hypothesize that the gap is due to the gravitational effects of planets, and that AB Aur is the forerunner of a β Pic-type system.

1 Introduction

In previous modeling studies, broad mid-infrared dips in the spectral energy distributions (SEDs) of some T Tauri stars have been attributed to physical gaps in the circumstellar disks, assuming that temperature decreases monotonically outwards from the star (Marsh & Mahoney 1992, 1993). Such gaps might be expected as a consequence of planet formation (Artymowicz 1987). Some Herbig Ae stars also exhibit mid-infrared spectral dips, and have other spectral characteristics which suggest that they are simply hotter (and more massive) versions of T Tauri stars (Hillenbrand et al. 1992). We would therefore expect gaps to be present in these disks also, but on larger scales than for the T Tauri stars. For example, the SED of AB Aur suggests a gap diameter of about 50 AU. Motivated by this prediction, we have made images of AB Aur at 11.7 μm wavelength, with a spatial resolution of 0″.17, and will now discuss these observations.

2 Observations

Our observations of AB Aur were made on October 28, 1993, using the SpectroCam-10 imaging spectrometer (Hayward et al. 1993) on the Hale 5-m telescope, at 11.7 μm wavelength, with 0″.25 pixels. The diffraction limit (λ/D) was 0″.48. A modified chopping-and-nodding technique (Van Cleve et al. 1994) was used in order to facilitate removal of the sky background, with N-S displacement of on-source and off-source positions. Short integration times (1.025 s each, for on-source and off-source) were used to reduce the effects of seeing and telescope motion. Observations of α Tau and β Gem were made for calibration purposes. The total on-source integration time was 45.1 s for AB Aur, and 12.3 s each for α Tau and β Gem.

3 Analysis Procedure

The analysis procedure was as follows:

1. Difference the raw images to subtract the sky background.

2. Combine the individual differenced images into a single, well-sampled, diffraction-limited image. In order to accomplish this, knowledge of the frame-to-frame offsets was required. These were estimated by maximizing the correlation between each differenced image and the nominal point spread function (PSF). The images were then combined using a most-probable Bayesian estimator, based on Gaussian prior statistics. The motivation for using this procedure, rather than simple "shift-and-add," is that the latter would have suffered from aliasing problems due to the slight undersampling at the focal plane. In the Bayesian procedure, the frame-to-frame Offsets effectively provide sub-pixel sampling which prevents aliasing of the diffraction-limited image. The result for AB Aur is shown in Figure 1a.

3. Estimate the true PSF using the calibrator-star observations.

4. Deconvolve the PSF from the combined AB Aur image, using a Bayesian estimator designed to obtain superresolution from the incorporation of prior information, specifically, the positivity of intensity and the finite support of the emission.

The deconvolution technique, described in more detail by Richardson and Marsh (1983), yields the most probable image conditioned on the measurements, based on *a priori* statistical models for both the measurement noise (zero-mean Gaussian) and the ensemble of possible images (zero-mean Gaussian for positive pixel-values and zero probability otherwise). Tests with both real and synthetic data indicate that with an input S/N $\sim$ 100 (the approximate value for the present observations), the spatial resolution of the deconvolved image is approximately 0.35 λ/D, i.e. $0\farcs17$, corresponding to 27 AU at the 160 pc distance of AB Aur (Hillenbrand et al. 1992).

A variety of different PSFs was used in the deconvolution, in order to investigate the sensitivity of the result to PSF errors. These PSFs were derived using (a) all available calibrator observations, (b) α Tau only, and (c) β Gem only. As an example, the first of these PSFs is shown in Figure 1b.

4 Results

The resulting deconvolved images of AB Aur, made with the above three PSFs, are shown in Figure 2 (a,b,c, respectively). Also shown (Figure 2d) is the result of yet another PSF, estimated using only the "sharpest" half of the α Tau and β Gem data (based on a sharpness index defined as the normalized sum of squares of pixel values). We regard Figure 2d as our best estimate of the AB Aur image. The peak brightness temperature was 176 K.

Also shown in Figure 2 are the deconvolved images of the calibrator stars, as an independent check on deconvolution performance. Figures 2e and 2f show, respectively: β Gem (deconvolved using the α Tau PSF) and α Tau (deconvolved using the β Gem PSF).

Figures 2a and 2d suggest that the AB Aur disk is extended ($\sim$50 AU) at 11.7 μm, and possesses a central depression of diameter $\sim$ 30–40 AU. Although of lower quality, images 2b and 2c support these conclusions. Further evidence of the reality of the central depression is that the calibrator-star images (Figures 2c, 2f) are single-peaked. They are distorted, however, due to seeing-induced PSF rows; comparison with the corresponding AB Aur images (Figures 2b, 2c), made with the same two PSFs, shows consistent behavior with respect to the geometric nature of the distortions. We have repeated the deconvolutions after dividing the AB Aur data set up in various ways, and have concluded that the main features of the image (the extended geometry and central depression) are real.

5 Interpretation

It is interesting to compare these imaging results with theoretical expectations based on modeling of the SED. Following previous work (Mathieu, Adams, & Latham 1991; Marsh & Mahoney 1992, 1993), we assumed a circumstellar disk model with a radial temperature law of the form $T(r) \propto$ r’, and a radial variation of line-of-sight optical depth of the form $\tau(r) \propto$?“$-\frac{7}{4}$, in which allowance was made for the presence of a gap. The frequency-dependence of dust opacity was assumed to be of the form given by Adams & Shu (1986), modified in the 8–13 μm region according to Cohen & Witteborn (1985). In the model, the silicate emission feature was assumed to be produced in an optically-thin dust cloud located in the gap region, with a dust temperature of 500 K, and a 9.7 μm optical depth of 0.1 (Cohen & Witteborn 1985). Stellar parameters (L_*, T_*, & A_V) were taken from Hillenbrand et al. (1992).

Figure 3 shows the observed SED, together with the theoretical spectrum for a model disk of inner and outer radii r_{in} = 0.19 AU and r_{out} = 106 AU, respectively, containing a gap between radial distances 0.28 AU and 25 AU. The assumed orbital inclination was 55°, and other parameters were: $T(r_{in}) = 2200$ K, $q = 0.58$, $\tau(r_1) = 2.8 \times 10^7$. The corresponding spatial intensity distribution of this model at 11.7 μm is shown as an inset, together with the "smoothed" version obtained by convolution with the spatial response of our superresolution algorithm. A comparison with Figure 2d shows that the model has reproduced the principal qualitative features of the observed (deconvolved) image, characterized by a central depression which is flanked by emission peaks separated by about 40 AU. The central source (inner-disk + star) has been diluted out in the smoothing process. It is encouraging that the peak brightness temperature of the smoothed model-image (169 K) is close to the observed value of 176 K.

In order to produce the central depression in the model image, it was necessary to locate the optically-thin silicate-emitting grains in an annulus around the outside edge of the gap, 23–25 AU from the star, leaving the region r = 0.28–23 AU devoid of material. We assume that these grains are heated beyond the local radiation temperature as a result of departures from blackbody emission, as would be expected if the grain size were small (Backman & Paresce 1992). For AB Aur, grains typical of the ISM would attain the required temperature of 500 K.

6 Discussion

The comparison of our observed images with theoretical models suggests that much of the inner region of the AB Aur disk has been swept clean of dust. We may therefore be witnessing, for the first time, one of the predicted observational consequences of planet formation near a newborn star. It is interesting that a recent observation of the circumstellar disk of the nearby main-sequence star β Pic (Lagage & Pantin 1994) also provides evidence for a central clearing. Since β Pic and AB Aur are of fairly similar spectral type (A5 and A0, respectively), it seems reasonable to suppose that AB Aur represents an earlier evolutionary stage of a β Pic-type system.

We thus have two classes of object (i.e., nearby main-sequence stars and Herbig Ae stars) whose circumstellar disks can be imaged in the mid-infrared with sufficient resolution to detect structure related to planet formation. Although the best linear resolution (in AU) would be obtained for the closest objects, β Pic appears to be unique in being the only nearby main-sequence star whose circumstellar disk is bright enough for detailed imaging. In contrast, there exists a substantial number of Herbig Ae stars whose disks could be imaged using the techniques described in this *Letter*.

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Figure Captions

Figure 1 (a) Combined (diffraction-limited) image of AB Aur; **(b)** PSF, derived from all available observations of α Tau and β Gem. Both images are presented on a logarithmic intensity scale of 2 decades, with a field of view of 3".

Figure 2 Deconvolved images at 11.7 μm, each presented on a linear intensity scale, with a field of view of 1".

(a) AB Aur, deconvolved using PSF derived from **all** calibrator data.

(b) AB Aur, deconvolved using PSF derived from α Tau observations only.

(c) AB Aur, deconvolved using PSF derived from β Gem observations only.

(d) AB Aur, deconvolved using PSF derived from the "sharpest" half of the α Tau and β Gem data.

(e) β Gem, deconvolved using PSF derived from α Tau observations.

(f) α Tau, deconvolved using PSF derived from β Gem observations.

Figure 3 Results of theoretical modeling.

Plot: Observed and modeled spectral energy distributions of AB Aur. The plotted points represent published photometry, taken from Hillenbrand et al. (1992) and Cohen & Witteborn (1985). The solid line represents the theoretical spectrum for a model consisting of star + circumstellar disk, in which the disk contains a gap. Also shown are the individual contributions of star (dot-dashed), and disk (dashed).

Inset: The upper panel shows the theoretical intensity distribution corresponding to the model. It is presented on a logarithmic scale spanning 6 decades, such that the peak intensity occurs at the central source (seen as a small dot), while the minimum intensity occurs at the outside edge of the disk as seen in the figure. The lower panel (linear intensity scale) shows the result of smoothing this distribution with the spatial response of our superresolution algorithm, and regridding using the same sampling interval as for Figure 2. The field of view of both panels is 1"

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