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SPIRAL STRUCTURE IN THE CIRCUMSTELLAR DISK AROUND AB AURIGAE[1]

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ABSTRACT

We present a near-infrared image of the Herbig Ae star AB Aur obtained with the Coronagraphic Imager with Adaptive Optics mounted on the Subaru Telescope. The image shows a circumstellar emission extending out to a radius of $r = 580$ AU, with a double spiral structure detected at $r = 200$–450 AU. The surface brightness decreases as $r^{-3.0\pm0.1}$, steeper than the radial profile of the optical emission possibly affected by the scattered light from the envelope surrounding AB Aur. This result, together with the size of the infrared emission similar to that of the ^{13}CO ($J = 1$–0) disk, suggests that the spiral structure is indeed associated with the circumstellar disk but is not part of the extended envelope. We identified four major spiral arms, which are trailing if the brighter southeastern part of the disk is the near side. The weak gravitational instability, maintained for millions of years by continuous mass supply from the envelope, might explain the presence of the spiral structure at the relatively late phase of the pre–main-sequence period.

Subject headings: planetary systems: protoplanetary disks — stars: individual (AB Aurigae) — stars: pre–main-sequence

1. INTRODUCTION

Protoplanetary disks are now believed to be ubiquitous, with a remarkable diversity. Their investigation has come to be essential for understanding the formation mechanism of planetary systems, since the diversity of disks could be relevant to the diversity of extrasolar planets. We need a spatial resolution of at least ~0".1 in order to resolve the disk morphology even for nearby star-forming regions at $d \sim 150$ pc. Recent high-resolution imaging studies with the *Hubble Space Telescope* (*HST*) revealed various disk morphologies around young stellar objects with several million years of age (e.g., Clampin et al. 2003; Grady et al. 2001). Such high resolution can be achieved even from the ground by using adaptive optics (AO) on a large telescope. In this Letter, we present a near-infrared (NIR) image of AB Aur, a Herbig Ae star, at a resolution of 0".1 obtained with the Coronagraphic Imager with Adaptive Optics (CIAO; Tamura et al. 2000) mounted on the 8.2 m Subaru Telescope atop Mauna Kea.

AB Aur ($d = 144^{+23}_{-17}$ pc; A0 Ve, van den Ancker et al. 1997) is one of the best-studied Herbig Ae/Be stars, with a mass of $2.4 \pm 0.2\ M_{\odot}$ and an age of 4 ± 1 Myr (deWarf et al. 2003). The circumstellar structure around AB Aur consists of two components: a compact rotating disk and an extended (>1000 AU) nebulosity or envelope surrounding the central disk. Mannings & Sargent (1997) detected a rotating disk of 450 AU in radius in the ^{13}CO ($J = 1$–0) line. The disk mass was estimated to be $0.02\ M_{\odot}$ from the millimeter continuum flux (Mannings & Sargent 1997; Henning et al. 1998). The extended reflection nebulosity was observed in its optical image (e.g., Nakajima & Golimowski 1995), indicating that AB Aur possesses abundant envelope material despite its relatively old age. High-resolution optical observations of AB Aur with the *HST* revealed that the inner part of the circumstellar material, at a size similar to that of the ^{13}CO disk, has a spiral band structure (Grady et al. 1999), although the spiral pattern was not very clearly visible possibly because the scattering emission from the more extended material mingles with it. Thanks to the small optical depth to the low-density extended envelope, the NIR image presented here shows only the structure coincident with the millimeter disk without contamination from the scattering envelope.

2. OBSERVATIONS AND DATA REDUCTION

We carried out *H*-band imaging of AB Aur on 2004 January 8 and 11 using CIAO mounted on the Subaru Telescope. The pixel scale was 21.33 ± 0.02 mas pixel^{-1} on the 1024×1024 InSb ALADDIN II array. An occulting mask of 0".6 diameter was employed so that the circumstellar emission could be imaged even in the close vicinity of the star within 1" (=144 AU) in radius, yet the halo of AB Aur was not saturated with 1 s exposure. We used a circular Lyot stop to block out the outer 20% of the pupil diameter.

We obtained two image data sets of AB Aur on January 8. The total exposure time for the first data set was 8.9 minutes with 81 frames, each of which was taken by co-adding 20 exposures of 0.33 s. The other data set was for 10.6 minutes with 108 frames, each taken by co-adding six exposures of 1 s. SAO 57754 was observed for 5.2 minutes as a point-spread function (PSF) reference star between the two AB Aur obser-

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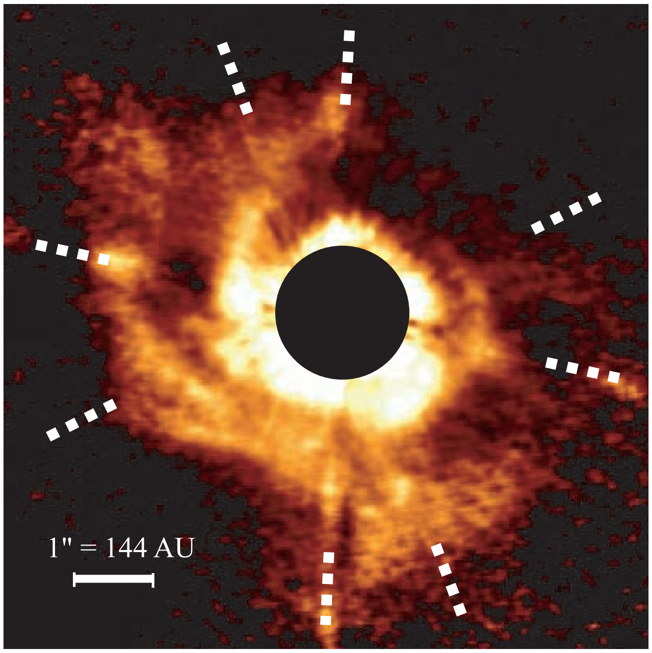

FIG. 1.—*H*-band image of the circumstellar structure around AB Aur after a reference PSF was subtracted. The surface brightness is multiplied by the distance squared from the center for display so that the fainter outskirts can be viewed with a high contrast. Boxcar smoothing is applied with 5 × 5 pixels. Directions of the spider patterns are indicated by dashed lines. The inner area of 1″.7 diameter ($r < 120$ AU; *filled circle*) is photometrically unusable and is masked. The field of view is 8″ × 8″. North is up, and east is to the left.

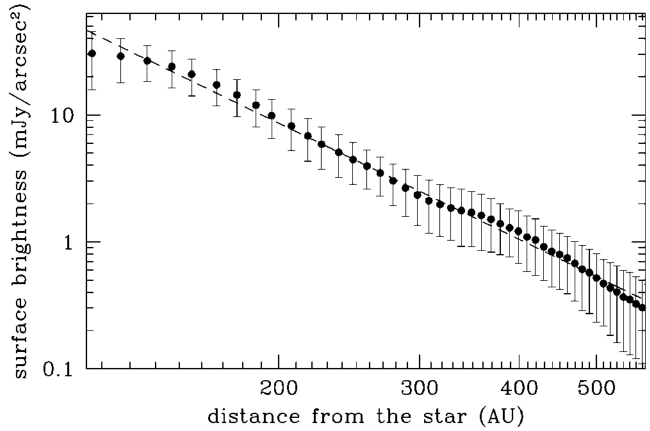

FIG. 2.—Azimuthally averaged radial profile of the surface brightness (*filled circles*) after the assumed inclination of $i = 30°$ was corrected. Error bars show the dispersion of brightness over the azimuth of 360° and radial width of 10 AU (0″.07). The dashed line indicates a power-law fit with an index of −3.0 to the brightness over the radial range between 120 and 580 AU.

vations. The signal-to-noise ratio of the reference star PSF was greater than 3 at $r < 6''$, as was similar to that of the AB Aur data. FS 111 was observed immediately before AB Aur and was used as a photometric calibrator (Hawarden et al. 2001). The sky was clear, and the natural seeing size was 0″.5. The spatial resolution achieved with the AO system (Takami et al. 2004) was 0″.10 (FWHM), which was measured with the Lyot stop in the optical path toward an unmasked star in the frames of SAO 57754.

At the second observing run on January 11, the seeing size and eventually the resolution with AO were a little worse and variable, although the sky was clear. Hence we used 62 frames that had resolutions similar to those obtained in the first run. The total exposure time was 6.2 minutes for the 62 frames, each taken by co-adding six exposures of 1 s. SAO 57393 was observed immediately before and after AB Aur as a PSF reference, with the total exposure time of 9.0 minutes.

The obtained frames were calibrated in the standard manner using IRAF: dark subtraction, flat-fielding with sky-flats, bad-pixel substitution, and sky subtraction. A reference star PSF was made by combining frames for either SAO 57754 or SAO 57393 depending on the observing date. We subtracted the reference star PSF from the image of AB Aur in order to detect faint structure buried in its halo. After shifting, rotating, and scaling the PSF so that its peak position, spider pattern, and halo brightness match those of each object frame, we made PSF-subtracted frames and combined them to produce the final image (see Itoh et al. 2002). We applied this subtraction method separately to the data obtained on January 8 and 11, confirming that the images taken on both nights were consistent with each other even if the reference stars and seeing conditions were different.

3. RESULTS

3.1. *Scattered Light from the Disk*

Figure 1 is the resultant *H*-band image after the PSF subtraction. We detected an extended emission seen from the edge of the occulting mask ($r \sim 60$ AU) out to the radius of 580 AU (= 4″.0), where the brightness drops to the detection limit of 0.3 mJy arcsec^{-2}. Figure 2 shows an azimuthally averaged radial brightness profile of the image deprojected with the assumed inclination of 30° and major-axis position angle of 58° (see below), showing that the surface brightness decreases as $r^{-3.0\pm0.1}$ with the radius r from 120 to 580 AU. The power-law dependence revealed in this study is steeper than that of r^{-2} for the optical nebulosity (Grady et al. 1999). The steeper slope in the NIR suggests that the detected light originates mainly from the disk itself without being significantly contaminated by the scattering emission in the envelope, which shows a shallower slope (Grady et al. 1999). This is also justified by the fact that the NIR scattering emission has a size similar to that of the ^{13}CO disk (Mannings & Sargent 1997).

We integrated the scattered light over the radial range of 120 AU $\le r \le$ 580 AU and calculated the ratio of the scattered to total fluxes as $F_{\rm disk}/F_{\rm total} = (1.2 \pm 0.2) \times 10^{-2}$, adopting the total flux $H = 5.1$ mag of AB Aur (Hillenbrand 1992). The *H*-band flux ratio is comparable to those of (2–4) × 10^{-2} measured over similar, or even inner, radial ranges of optically thick disks around other young stars with similar ages (HD 100546, Augereau et al. 2001; TW Hya, Weinberger et al. 2002; GM Aur, Schneider et al. 2003). The large scattered light flux is qualitatively accounted for if the disk around AB Aur is flared to receive sufficient light from the central star and a large amount of dust particles contributing to the scattering at 1.6 μm are present at the disk surface (e.g., Whitney & Hartmann 1992). This is consistent with a flared disk geometry suggested by model fitting to the mid- and far-infrared spectral energy distribution (SED) of AB Aur (Dominik et al. 2003).

Assuming that the emission comes from a tilted disk with a circularly symmetric brightness distribution and applying an ellipse isophoto fitting at the radii between $r = 1''.4$ and $1''.8$, we derived the inclination and position angle of the major axis as $i = 30° \pm 5°$ and P.A. = 58° ± 5°, respectively. The presence of spiral arms (see § 3.2) in this radial range does not significantly affect the derivation of the geometry of the NIR disk, because the fitting applied to inner and outer regions gave consistent results. It should be noted, however, that any intrinsic brightness distribution asymmetry that makes the northwestern part darker, as may be the current case caused by an anisotropic scattering phase function, does affect the inclination. The inclination of 30° should be taken as an upper limit in such a case.

The derived inclination agrees well with the recent NIR interferometric measurements for the inner ($r \sim 0.5$ AU) disk (Eisner et al. 2003; Millan-Gabet, Schloerb, & Traub 2001) and with the constraint (less than 45°) obtained by the optical imaging with the *HST*/Space Telescope Imaging Spectrograph (STIS; Grady et al. 1999). It is, however, significantly smaller than 76° estimated from the ^{13}CO observations by Mannings & Sargent (1997). The position angle of the major axis is also different from that of the millimeter measurement (P.A. = 79°) by 20°. Lower spatial resolutions of millimeter observations may have caused such discrepancies, and higher resolution imagings of the thermal emission are necessary for obtaining more precise constraints on the disk geometry. On the other hand, the STIS optical image (Grady et al. 1999) lacks a distinguishable axis, not showing any clear ellipticity. Because the image shows a nebulosity much more extended and more circularly distributed than the NIR image, the optical flux may be dominated by scattering from the region with a large-scale height especially at large radii. The STIS wedge occults the region exactly along the derived major axis, which also makes it difficult to identify a distinguishable axis in the image.

3.2. *The Spiral Structure*

The *H*-band image in Figure 1 shows a remarkable spiral pattern at $r = 200$–450 AU. The spiral pattern coincides with the spiral band structure seen in the optical image taken with the *HST* (Grady et al. 1999). The new image has, however, revealed the entire spiral pattern located in the inner part (200 AU $\lesssim r \lesssim$ 300 AU). In addition, it clearly shows the spirals with a high contrast because the scattered light from the surrounding envelope is negligible; the spiral pattern is associated with the circumstellar disk but not with the envelope. This is indeed the first case in which a spiral pattern, not a ring or a circular gap, has been detected in the NIR around a young star, although it was detected in the optical image of HD 100546 (Grady et al. 2001) as well as AB Aur.

The southeastern part is brighter, which suggests that this part is the near side of the disk if we assume that forward scattering is dominated as is the case of Mie scattering. The observed winding direction of the spiral pattern projected on the disk is S-wise, not Z-wise. These results, combined with the velocity field of the disk in which the northeastern part is blueshifted and the southwestern part is redshifted (Mannings & Sargent 1997), mean that the arms are trailing.

Figure 3 shows a deprojected image of Figure 1 with some of the features identified. We can see inner and outer spiral arms especially at the eastern half of the disk where the presence of a dark lane makes the double-arm structure evident. The inner arm located at $r \sim 230$ AU running from the east to northeast is the brightest. The outer arm running from the south to northeast is traced at $r \sim 330$ AU with a branch and a knotty structure. On the western side of the disk, a fainter arm is seen at $r \sim 260$ AU, and another outer arm at $r \sim 440$ AU in the southwest is largely open to the south.

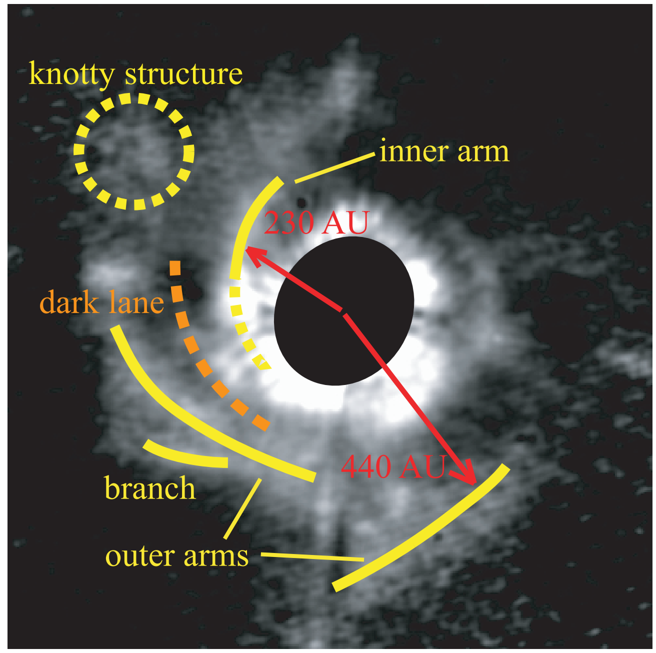

FIG. 3.—Same as Fig. 1, but the image is deprojected with an assumed inclination of 30° to show the "face-on" view of the AB Aur disk. Some of the major features are identified.

4. DISCUSSION

What is the mechanism to excite and maintain the spiral structure in the disk of AB Aur, a single star with the age of 4 Myr? Theoretical calculations show that a forming planet located in a disk opens a gap (Takeuchi, Miyama, & Lin 1996) that is often associated with a spiral structure extending inward and outward into the disk from the planet (e.g., Bate et al. 2003). If the dark lane at $r \sim 300$ AU is a gap where an unseen companion is located, its mass must be less than $10M_J$, which is estimated from the evolutionary tracks given by Burrows et al. (1997) and Allard et al. (2001) in order to be consistent with the detection limit of $H \sim 16.5$ mag in the interarm region. The main structure that we may observe in a disk, however, would be a circular gap but not a spiral structure such as the one revealed in this study if there is an unseen companion, because matter is cleared away in the gap while the spiral pattern is merely the density fluctuation of matter. It is therefore not probable that the spiral structure is produced by an unseen companion.

On the other hand, the gravitational instability may excite the spiral structure without any gap in a disk. According to theoretical studies (e.g., Nelson et al. 1998), spiral structure is produced and sustained if a circumstellar disk has the minimum Q-value of $1.5 \lesssim Q \lesssim 2.0$, where $Q = c_S\Omega/(\pi G\Sigma)$ is Toomre's Q parameter with c_S, Ω, and Σ being the sound speed, angular velocity, and surface density, respectively. Because Q is minimized at the outer edge of a disk for the standard model (D'Alessio et al. 1998), we evaluate Q at the outermost arm radius $r = 450$ AU in order to see if the gravitational instability occurs. Taking the disk mass of 0.02 $M_\odot$ (Mannings & Sargent 1997; Henning et al. 1998) and the radial dependence of surface density as $\Sigma \propto r^{-0.5}$, as observed for several T Tauri disks (Kitamura et al. 2002), with $c_S = 0.23$ km s^{-1} ($T = 15$ K; Miroshnichenko et al. 1999) and the assumed Kepler rotation, we obtain $Q \sim 17$ at $r = 450$ AU. If we take a larger disk mass of 0.15 $M_\odot$, as derived if we use the opacity in Pollack et al. (1994) for smaller dust particles (Bouwman et al. 2000), we obtain $Q \sim 2$. Although the value of Q has a large uncertainty as estimated above, the smaller value of Q may allow the spiral structure to be excited in the disk.

The presence of spiral structure around the star with the age of 4 Myr suggests that the structure is maintained for $\sim 10^6$ yr, much longer than the dynamical timescale of 10^4 yr at $r = 450$ AU. The present mass accretion rates from disks onto stars are derived to be $\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ from UV spectra of Herbig Ae/Be stars, including AB Aur (Miroshnichenko et al. 1999). This small value, if constant, may allow the disk to keep sufficient mass for instability for $\sim 10^6$ yr. In addition, AB Aur could have the accretion rate of $\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ from its halo, as Miroshnichenko et al. (1999) estimated from their SED fitting. The mass supply from the envelope of AB Aur may thus be sufficient to replenish the disk to sustain the spiral structure. Another single Herbig Ae/Be star HD 100546 also shows a spiral disk with a surrounding envelope (Grady et al. 2001), giving support to the possibility that the mass supply from envelopes contributes to the spiral instability.

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