A KEPLERIAN DISK AROUND THE HERBIG Ae STAR HD 169142

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Received 2005 September 19; accepted 2005 December 16

ABSTRACT

We present Submillimeter Array observations of the Herbig Ae star HD 169142 in 1.3 mm continuum emission and $^{12}\text{CO } J = 2-1$ line emission at $\sim 1''.5$ resolution that reveal a circumstellar disk. The continuum emission is centered on the star position and resolved, and it provides a mass estimate of $\sim 0.02 M_{\odot}$ for the disk. The CO images show patterns in position and velocity that are well matched by a disk in Keplerian rotation with low inclination to the line of sight. We use radiative transfer calculations based on a flared, passive disk model to constrain the disk parameters by comparison to the spectral line emission. The derived disk radius is 235 AU, and the inclination is 13° . The model also necessitates modest depletion of the CO molecules, similar to that found in Keplerian disks around T Tauri stars.

Key words: planetary systems: protoplanetary disks — stars: individual (HD 169142) — stars: pre-main-sequence

Online material: color figure

1. INTRODUCTION

Millimeter-wave observations of disks surrounding pre-main-sequence stars are a promising probe of the planet formation process (Beckwith & Sargent 1996). While most studies have concentrated on the circumstellar disks around low-mass T Tauri stars, far less is known about the disks around their intermediate-mass counterparts, the Herbig Ae/Be stars. Better characterization of the circumstellar disks around these higher mass stars will help address how stellar mass affects the development of planetary systems.

Detailed modeling of the spectral energy distributions of Herbig Ae/Be stars has generally supported the protoplanetary disk paradigm (e.g., Hillenbrand et al. 1992; Chiang et al. 2001; Dominik et al. 2003). But out of the large sample of Herbig Ae/Be star disk candidates recognized by infrared excess from circumstellar dust (Thé et al. 1994; Malfait et al. 1998), only a handful have been spatially and spectrally resolved through direct imaging observations to show clear signatures of rotationally supported disks of solar system size (Mannings & Sargent 1997, 2000; Piétu et al. 2003; Corder et al. 2005).

The emission-line star HD 169142 (SAO 186777, MWC 925; spectral type A5) with infrared excess (IRAS 18213–2948) was included in the Thé et al. (1994) catalog of 287 Herbig Ae/Be candidates. Subsequent photometric and spectroscopic observations filled out its spectral energy distribution at infrared and submillimeter wavelengths (Sylvester et al. 1996; Dunkin et al. 1997; Malfait et al. 1998). At ~ 145 pc distance, HD 169142 is notably isolated from any molecular cloud or extensive reflection nebula, although Kuhn et al. (2001) used differential polarimetry to detect an ~ 200 AU ($\sim 1''.5$) diameter circular halo of scattered light. While some doubt lingers as to the pre-main-sequence nature of HD 169142, it is among isolated Herbig Ae stars selected by Meeus et al. (2001) and classified as “group Ib” with a strong mid-infrared component and a conspicuous absence of $10 \mu\text{m}$ silicate emission (Bouwman et al. 2001). This star also has prominent

polycyclic aromatic hydrocarbon emission features (Habart et al. 2006).

The spectral energy distribution of HD 169142 is well fitted by a passive irradiated disk model, although the near-infrared flux seems low, perhaps because the inner disk rim is viewed pole-on (Dominik et al. 2003) or perhaps because extensive inner disk clearing is under way, possibly together with planet formation. The relative isolation of this star from any molecular clouds may indicate an advanced pre-main-sequence age. A circumstellar molecular component is detected via relatively strong emission in the CO $J = 3-2$ line, with the narrow CO line profile modeled with a near face-on disk (Greaves et al. 2000; Dent et al. 2005).

Here we present high-resolution observations of HD 169142 from the Submillimeter Array⁴ (SMA) that clearly resolve a circumstellar disk in Keplerian rotation. We derive the basic disk properties from arcsecond-resolution images of the $^{12}\text{CO } J = 2-1$ line using radiative transfer calculations based on a flared, passive disk model (D’Alessio et al. 2005).

2. OBSERVATIONS

We used the SMA (Ho et al. 2004) to observe HD 169142 on 2005 April 19. Table 1 lists the observational parameters. Seven antennas were available in an extended configuration that provided a baseline range of 27–181 m and a synthesized beam of $1''.6 \times 1''.0$ at position angle 20° . The target source was tracked over the hour angle range -1.0 to 3.5 . Weather conditions were excellent, and system temperatures ranged from 85 to 150 K (double sideband). The correlator provided 2 GHz of bandwidth in each sideband and was configured to include the $^{12}\text{CO } J = 2-1$ line at 230.538 GHz in the upper sideband in a 104 MHz spectral “chunk” with channel spacing of 0.2 MHz ($\sim 0.27 \text{ km s}^{-1}$). Complex gain calibration was performed using the calibrator sources J1911–201 and J1924–292. Passband calibration was done with observations of the strong sources 3C 279 and Uranus. The absolute flux scale was set using observations of Callisto and is estimated to be accurate to about 10%. All of the calibration was done

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⁴ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

TABLE 1
HD 169142 OBSERVATIONAL PARAMETERS

Parameter	Value
Observations.....	2005 April 19 (seven antennas)
Pointing center (J2000.0).....	$\alpha = 18^{\text{h}}24^{\text{m}}19^{\text{s}}.78$, $\delta = -29^{\circ}46'49''.37$
Min/max baseline.....	27–181 m
Flux calibrator.....	Callisto
Primary beam HPBW.....	55"
Synthesized beam HPBW.....	$1''.6 \times 1''.0$, P.A. 20°
K Jy $^{-1}$	15.4
Spectral line setup.....	512 channels, 104 MHz
Transition, frequency.....	$^{12}\text{CO } J = 2-1$, 230.538 GHz
Channel spacing.....	0.27 km s $^{-1}$
rms (line images).....	180 mJy
rms (continuum).....	2.7 mJy

using the MIR software, followed by standard imaging and visual analysis using the MIRIAD package.

3. RESULTS AND DISCUSSION

3.1. Continuum

The lower right panel of Figure 1 (*top*) shows the continuum image made from the upper sideband visibility data. Fitting an elliptical Gaussian to the visibilities gives a flux of 169 ± 5 mJy and a FWHM size of $\sim 0''.9$. The fit does not indicate any significant ellipticity. The observed flux is consistent with the previous single-dish 1.3 mm measurement of 197 ± 15 mJy (Sylvester et al. 1996), taking into account the uncertainties, which suggests that the interferometer is not missing any large-scale emission. The 1.3 mm continuum emission arises from a compact region, which we associate with the circumstellar disk. The spectral energy distribution indicates that thermal dust emission strongly dominates at this wavelength; any contribution from ionized gas emission is negligible.

The dust continuum flux, S_{ν} , may be used to estimate the disk mass, M_{disk} , assuming optically thin emission, i.e., $M_{\text{disk}} = S_{\nu} D^2 / \kappa_{\nu} B_{\nu}(\langle T \rangle)$, where B_{ν} is the Planck function. We adopt the mass opacity of Beckwith et al. (1990), $\kappa_{\nu} = 0.02$ (1.3 mm λ^{-1}) cm 2 g $^{-1}$, which includes a gas-to-dust ratio of 100. Assuming an average temperature $\langle T \rangle = 30$ K, appropriate for the bulk of the disk material, the disk mass is $0.02 M_{\odot}$. The factor of a few uncertainty in κ_{ν} likely dominates the uncertainty in this mass estimate. This mass estimate falls in the middle of the range of estimates for protoplanetary disks around T Tauri stars.

3.2. $^{12}\text{CO } J = 2-1$

Figure 1 (*top*) shows the $^{12}\text{CO } J = 2-1$ line emission distribution over the velocity range with significant emission. The images show an approximately symmetric pattern around the central velocity of 6.8 km s $^{-1}$. At the extremes, the emission is centered at the continuum peak position, while at intermediate velocities the emission shows a gradient oriented slightly east of north that separates into two peaks at the central velocities. Figure 2 shows the spectrum of the $^{12}\text{CO } J = 2-1$ line convolved to a beam size of $3''.5$, which encompasses the full spatial extent of the emission. The spectral profile is double-peaked. All of these features taken together strongly suggest a disk at low inclination to the line of sight in Keplerian rotation, as calculated by Beckwith & Sargent (1993), where low J CO lines have high optical depth and trace the gas temperature near the disk surface. A Keplerian velocity field is appropriate for the estimated low disk mass relative to the central star mass, i.e., $M_{\text{disk}} (\approx 0.02 M_{\odot}) \ll M_{\text{star}} (\approx 2.0 M_{\odot})$.

FIG. 1.—*Top*: Series of $^{12}\text{CO } J = 2-1$ line velocity images of HD 169142, with the 1.3 mm continuum image at the lower right. The contour levels for the line images are $-2, 2, 4, 6, \dots \times 200$ mJy. Negative contours are dotted. The small cross marks the position of the continuum peak. The contour levels for the 1.3 mm continuum image are $5, 10, 15, \dots \times 5$ mJy. The filled ellipse in the lower left corner of the upper left panel shows the $1''.6 \times 1''.0$ P.A. 20° synthesized beam. *Middle*: The $^{12}\text{CO } J = 2-1$ line velocity images for the best-fit disk model (see text). The contour levels are the same as in the top panel. *Bottom*: Difference images formed from the subtraction of the best-fit model visibilities from the observations. The contour levels are the same as in the top panel. [See the electronic edition of the Journal for a color version of this figure.]

3.2.1. Disk Model

In order to verify the Keplerian nature of the observed rotation of the outer disk material and to provide quantitative constraints on the basic disk parameters, we performed a series of radiative transfer calculations based on a physical model selected from the catalog of irradiated accretion disk models of D'Alessio et al. (2005). We selected the model that Dent et al. (2006) found to closely match the spectral energy distribution of HD 169142. In this model, the central star parameters are $T_{\text{eff}} = 9000$ K, $M_{*} = 2.0 M_{\odot}$, $R_{*} = 1.7 R_{\odot}$, and age = 10 Myr, which are well matched to the stellar properties of HD 169142. The disk has a mass accretion rate of $1.0 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, with a viscosity parameter $\alpha = 0.01$. The dust in the disk is well mixed with the gas and has a

FIG. 2.—Spectrum of the $^{12}\text{CO } J = 2-1$ line observed from HD 169142 at the position of peak continuum emission convolved to a $3''.5$ beam size (histogram) and the best-fit disk model (solid line).

power-law size distribution $n(a) \sim a^{-p}$, $p = 3.5$, with sizes ranging from $a_{\min} = 0.005 \mu\text{m}$ to $a_{\max} = 1 \text{ mm}$.

We identified an optimal disk radius, inclination, and orientation on the plane of the sky, as well as CO abundance, by performing a χ^2 minimization, comparing the SMA visibility data and visibilities derived from a grid of disk models spanning a range for each parameter. The radiative transfer calculations were done with the two-dimensional accelerated Monte Carlo code of Hogerheijde & van der Tak (2000) to generate simulated data cubes from which visibilities were derived at the (u, v) points observed by the SMA for the calculation of the χ^2 metric. The (dust) temperature and density values from the model were rebinned and truncated for a range of outer disk radii from 150 to 400 AU, based on the extent seen in the $^{12}\text{CO } J = 2-1$ images. Because of beam dilution, these data do not constrain the inner disk radius. The narrow line width suggests a viewing angle close to face-on for the disk, and we explored a range of inclinations from 0° to 30° . The turbulent component of the velocity field was fixed at the low value of 0.12 km s^{-1} , less than the resolution of the data. The CO abundance is characterized by a depletion factor from the nominal dark cloud abundance of 10^{-4} with respect to molecular hydrogen.

We find a best-fit disk model with radius $235 \pm 5 \text{ AU}$ and inclination $13^\circ \pm 1^\circ$, oriented at position angle $5^\circ \pm 5^\circ$, with a CO abundance of 2.5×10^{-5} (depletion factor of 4). We assign uncertainties to the fitted parameters that are somewhat larger than the formal uncertainties based on visual examination of the model images and their residuals. Table 2 summarizes the model parameters. Figure 1 (middle) shows the velocity channel maps from simulated observations of the best-fit model. The Keplerian disk model clearly captures the main features visible in the data.

TABLE 2
HD 169142 MODEL PARAMETERS

Parameter	Value
Physical structure.....	Irradiated accretion disk ^a
Velocity field.....	Keplerian rotation
Stellar mass.....	$2.0 M_\odot$
Turbulent velocity.....	0.12 km s^{-1}
Disk outer radius.....	235 AU
Inclination angle.....	13°
Disk P.A.....	5°
CO abundance.....	2.5×10^{-5}

^a D'Alessio et al. (2005).

Figure 2 shows the spectrum at $3''.5$ resolution derived from the model overlaid on the data. This comparison gives an impression of differences integrated over the full spatial extent of the disk emission. The derived low inclination is compatible with the lack of detectable ellipticity in the 1.3 mm dust emission, as well as the approximately circular appearance of the polarized scattered optical light nebula. The derived disk outer radius of 235 AU is larger than the 130 AU inferred from unresolved single-dish CO $J = 3-2$ data (Dent et al. 2005), although somewhat smaller than those found for other resolved pre-main-sequence A star systems—for example, 545 AU for MWC 480 (Simon et al. 2000) or 835 AU for HD 34282 (Piétu et al. 2003)—and comparable to some lower mass T Tauri star disks (Simon et al. 2000). The modestly depleted CO abundance in this disk is similar to the values typically found for the Keplerian disks around T Tauri stars, for example, 1.4×10^{-5} derived for the DM Tau disk by Dutrey et al. (1997).

The channel maps present minor asymmetries and irregularities that are not reproduced by the simple, smooth, Keplerian model. However, there are no dramatic departures from this equilibrium configuration like those seen in the circumstellar material around AB Aur, which is perhaps a considerably younger Herbig Ae star (Piétu et al. 2005; Corder et al. 2005). Figure 1 (bottom) shows images made from the difference between the disk model and the data for each channel. These difference images show faint, extended emission in the data at blueshifted velocities and slight excess in central peak brightness at redshifted velocities. These differences between the data and the model are not especially significant, but they may reflect real source structure. Observations with higher sensitivity and higher angular resolution will be needed to be more definitive.

4. CONCLUSIONS

We have imaged the Herbig Ae star HD 169142 in 1.3 mm continuum emission and $^{12}\text{CO } J = 2-1$ line emission at $\sim 1''.5$ resolution. These observations resolve a disk of molecular gas in Keplerian rotation around the star. The presence of the disk is strong evidence that HD 169142 is a bona fide pre-main-sequence star, despite its distance from any molecular cloud. The star's spectral energy distribution, its isolation, and the regularity of its disk velocity field suggest an advanced pre-main-sequence evolutionary state. The millimeter dust emission indicates a mass of $\sim 0.02 M_\odot$ for the disk. Modeling the CO line emission shows that the disk has an outer radius of 235 AU and is viewed close to face-on, compatible with an associated scattered light nebula seen with differential polarimetry. The disk mass, size, and CO depletion are in line with those found for resolved Keplerian disks around other young stars.

We thank Jim Moran, the SMA director, for allocating observing time to the Harvard University Astronomy 191 undergraduate class that allowed A. R. and M. L. to undertake this work. We thank Nimesh Patel for help with the observations and

Nuria Calvet for discussions about disk models and for pointing us to other work under way on HD 169142. We acknowledge NASA Origins of Solar Systems Program grant NAG5-11777 for partial support.

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