DISCOVERY OF AN EDGE-ON DISK IN THE MBM 12 YOUNG ASSOCIATION

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Received 2002 January 3; accepted 2002 April 15; published 2002 April 24

ABSTRACT

We report the discovery of a spatially resolved edge-on protoplanetary disk in the ~2 Myr old MBM 12 young association. Our near-infrared images of LkHα 263C (MBM 12A 3C), obtained with the Hokupa’a adaptive optics system on the Gemini North telescope, clearly show two elongated reflection nebulosities separated by a dark lane, a morphology well matched by scattered-light models of an optically thick (at near-infrared wavelengths) edge-on disk. An optical spectrum of the scattered-light nebulosity obtained with the Keck II telescope exhibits a spectral type of M0 ± 0.5 (T_eff = 3850 ± 100 K) for the central star and contains Hα and forbidden emission lines, which may indicate the presence of a jet. The absence of a near-infrared point source implies A_v > 9.5 toward the unseen central star. The disk is flared and has a radius of ~150 AU (at a distance of 275 pc) and an inclination of 87°. The aspect ratio of the model disk in the J band is 0.72. There is possible evidence of dust settling to the disk midplane. LkHα 263C is 4′115 from the 0′415 binary LkHα 263 A and B (MBM 12A 3A and 3B), which is itself 15′5 from LkHα 262 (MBM 12A 2). Thus, LkHα 263C may be the first disk to be clearly resolved around an individual star in a young quadruple system. The detection of a faint edge-on disk near a bright star demonstrates both the high angular resolution and the high sensitivity that can be achieved with adaptive optics imaging on large telescopes.

Subject headings: binaries: close — circumstellar matter — open clusters and associations: individual (MBM 12) — stars: pre–main-sequence — techniques: high angular resolution

1. INTRODUCTION

Planets form out of circumstellar disks. While a vast majority of very young stars show indirect evidence of disks, such as excess emission in the infrared (IR; e.g., Lada et al. 2000), only a handful have been imaged directly. Spatially resolved images are extremely valuable for investigating the structure and physical properties of protoplanetary disks as well as their subsequent evolution into planetary systems. Therefore, scattered-light disk images obtained by the Hubble Space Telescope (HST) have been the subject of intense scrutiny (e.g., O’Dell, Wen, & Hu 1993; Stapelfeldt et al. 1998; Padgett et al. 1999). Large ground-based telescopes equipped with adaptive optics (AO) systems are now able to achieve angular resolution and sensitivity comparable to that from space. Taking advantage of these new capabilities, we have initiated AO observations of nearby young star environs. Here we report the discovery of an edge-on disk in the MBM 12 young association.

MBM 12 (=L1457; Magnani, Blitz, & Mundy 1985) is one of the few clouds at high Galactic latitude known to harbor young stellar objects. Until recently, it was also considered to be the nearest molecular cloud to the Sun, at a distance of 50–100 pc (Hobbs, Blitz, & Magnani 1986; Hearty et al. 2000). However, a recent distance estimate by Luhman (2001), based on an alternate analysis of the data from those studies and a new comparison of M dwarfs in the foreground and background of the cloud with local field dwarfs, places MBM 12 at ~ 275 pc. A dozen young stars have been found in projection against the cloud and are believed to comprise a young association (MBM 12A; Luhman 2001 and references therein). The strengths of photospheric lithium absorption as well as the positions of MBM 12A stars on the H-R diagram suggest an age of ~2 Myr for the group. Mid-IR photometry of the original eight members reveal that six of them are surrounded by optically thick accretion disks (Jayawardhana et al. 2001). The disk fraction found in MBM 12A (~75%) falls in the middle of the range reported for other star-forming regions like Taurus and Trapezium (Lada et al. 2000 and references therein) but is significantly higher than in ~10 Myr old nearby groups such as the TW Hydrae Association (Jayawardhana et al. 1999). Given their relative proximity, MBM 12A stars are suitable targets for high-resolution studies of disks and close companions.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Adaptive Optics Imaging

The young stars LkHα 262 (MBM 12A 2) and LkHα 263 (MBM 12A 3), which form a wide binary system (15′5), were observed during the nights of 2001 October 8 and 2000 December 25, respectively, with the University of Hawaii Hokupa’a AO system in conjunction with the 1024 × 1024 array near-IR camera (Graves et al. 1998) on the Gemini North telescope. The H-band plate scale of QUIRC was 0′01998 ± 0′0008 pixel⁻¹ (F. Rigaut 2001, private communication), corresponding to a total field of 20′46 × 20′46. Short and long exposures were obtained for LkHα 262 at K' and for LkHα 263 at J, H, and K'. The observing and data reduction
procedures will be described in a later study. The unsaturated point sources in the final images of LkHα 263 exhibited FWHM = 0″.11 in J, 0″.096 in H, and 0″.09 in K′ and are used to estimate the point-spread function for the disk modeling discussed later in this work.

Gemini AO images of LkHα 262 and LkHα 263 are shown in Figure 1. Only one point source was found in the data for LkHα 262. LkHα 263 is resolved into a close binary (0″.4) with a fainter, extended companion (4″). Henceforth, we refer to the southwest and northeast components of the binary and the extended source as LkHα 263 A, B, and C (MBM 12A 3A, 3B, and 3C), in order of K′-band brightness.

Array coordinates and photometry for the A, B, and C components of LkHα 263 were measured with the IRAF tasks IMEXAMINE and PHOT, respectively. Aperture photometry for LkHα 263A and LkHα 263B was extracted with a radius of 6 pixels, which was chosen to be small enough to avoid significant contamination by the other component of the binary. These measurements were used to compute the flux ratio of the two stars in each band. Photometric calibration was derived by combining the J, H, and K′ measurements for LkHα 263A+B from the Two Micron All-Sky Survey (2MASS) with aperture photometry with a radius of 60 pixels for this system in Gemini short exposures. This calibration was then used to measure absolute photometry for LkHα 263C with an aperture radius of 40 pixels in the short and long exposures. The signal-to-noise ratio of LkHα 263C was low in the short exposures, but the photometric calibrator LkHα 263A+B was not saturated in those frames, allowing accurate (if not precise) photometry. Meanwhile, because the conditions were not photometric and because the calibration was derived from the short exposures, the accuracy of the measurements from the long exposures was compromised. After comparing the measurements from the long and short exposures, we arrive at the photometry for LkHα 263C that is listed in Table 1.

2.2. Optical Spectroscopy

We obtained an optical spectrum of LkHα 263C on 2001 November 13 with the Keck low-resolution imaging spectrometer (LRIS: Oke et al. 1995). The long-slit mode of LRIS was used with the 400 line mm−1 grating (λblue = 8500 Å) and GG495 blocking filter. The slit width was 1″0, producing a spectral resolution of FWHM = 6 Å. The exposure time was 600 s. After bias subtraction and flat-fielding, the spectrum was extracted and calibrated in wavelength with arc lamp data. The spectrum was then corrected for the sensitivity function, which was measured from observations of the spectrophotometric standard star Feige 110. The portion of the LRIS spectrum exhibiting spectral features is provided in Figure 2.

3. RESULTS

As shown in the Gemini AO images in Figure 1, LkHα 263C is extended and not associated with a point source at near-IR wavelengths. Instead, there are two parallel, elongated nebulosities separated by a narrow dark lane. The two nebulosities

| Component | Separation (arcsec) | Position Angle (deg) | J (mag) | H (mag) | K′ (mag) |
|-----------|---------------------|----------------------|--------|--------|--------|
| A .......... | ...                 | ...                  | 11.52  | 10.64  | 10.21  |
| B .......... | 0.415 ± 0.004       | 51.9 ± 0.1           | 11.25  | 10.51  | 10.34  |
| C .......... | 4.115 ± 0.02        | 58.3 ± 0.2           | 16.5 ± 0.15 | 16.0 ± 0.15 | 16.1 ± 0.3 |

Note.—The positions of B and C are measured with respect to A, and the photometry for A and B is computed by combining the photometry for A+B from 2MASS with the relative brightnesses of A and B in the AO images.
are about 1"1 (300 AU) in length. The southwest component is ≈20% brighter than its northeastern counterpart in H-band peak brightness. The morphology of LkHα 263C matches that expected for an optically thick circumstellar disk seen nearly edge-on. The central star is hidden behind the disk material, but its light is scattered by the upper and lower surfaces of the disk, producing the observed nebulosities. Similar nearly edge-on disks have been detected previously by HST, speckle, AO imaging around a number of young stars including HH 30 (Burrows et al. 1996), HK Tau B (Stapelfeldt et al. 1998; Koresko 1998), and HV Tau C (Monin & Bouvier 2000).

The spectrum in Figure 2 is useful in constraining the physical properties of LkHα 263C. Both photospheric absorption features (CaH, TiO, and Na) and a variety of forbidden emission lines ([O I], [O II], [N II], and [S II]) are detected. The continuum is well matched by a spectral type of M0 ± 0.5. The lack of reddening in the spectrum and the IR colors of LkHα 263C indicates that all of the detected light is scattered, which is consistent with the lack of a point source in the images. For a spectral type of M0 and an age of less than 3 Myr, the evolutionary models of Baraffe et al. (1998) imply a mass of ≈0.7 M⊙. Meanwhile, the composite of LkHα 263A+B exhibits a spectral type of M3 (Luhman 2001). Because these two objects have comparable brightnesses at IR wavelengths, they probably have similar spectral types and masses. If we assume that each has a spectral type of M3 and correct the bolometric luminosity of the composite system (Luhman 2001) for the binary, then they have masses of ≈0.45 M⊙ by the models of Baraffe et al. (1998). Thus, 3C is more massive than 3A and 3B, even though it is much fainter from our vantage point. The Hα and forbidden emission lines found in LkHα 263C have also been observed for other edge-on systems, such as HH 30 and HV Tau C (Kenyon et al. 1998; Magazzù & Martin 1994). Forbidden transitions are typical of Herbig-Haro objects, Class I sources, and some T Tauri stars, where the emission is believed to arise predominantly in jets (Kenyon et al. 1998 and references therein).

Now that we have an estimate of the mass of the central star in LkHα 263C, we can use the absence of a near-IR point source to arrive at a lower limit for the star’s line-of-sight reddening. After inserting artificial point sources of various brightnesses in the center of the dark lane in the deep K′ image, we find a detection limit of K′ ~ 19. Given the unreddened brightness of K = 9.5 for an M0 star at the age and distance of MBM 12A (e.g., LkHα 262), the unseen central star must have a reddening of |A_K| > 9.5. On the other hand, Luhman (2001) derived an extinction of |A_K| ~ 0 for the LkHα 263A+B binary, just 4" away. Thus, the extinction toward the C component must be almost entirely local, i.e., due to an edge-on optically thick disk blocking light from the central star.

4. DISK MODEL

We have attempted to fit a physical model to the disk around LkHα 263C, following the methods described in D’Alessio, Calvet, & Hartmann (2001). The model assumes complete mixing between dust and gas and solves for the vertical disk structure including the heating effects of stellar radiation as well as viscous dissipation in the disk itself. Figure 3 shows the comparison of the observations with the images of a disk model with an accretion rate of $5 \times 10^{-10} M_\odot$ yr$^{-1}$, viscosity parameter $\alpha = 0.01$, $T_\star = 3850$ K, $M_\star = 0.7 M_\odot$, $R_\star = 2.2 R_\odot$, a disk radius of 150 AU, and an inclination angle of 87°. The aspect ratio in the J-band model image is 0.72, considering the lowest contour plotted. The disk dust grains are assumed to have a power-law size distribution with an index of $-3.5$, a maximum particle radius of 1 mm, and abundances given by Pollack et al. (1994). The model disk has a mass of $0.0018 M_\odot$, although this estimate is highly sensitive to the assumed dust opacity. The model fit is by no means unique, and while the model shown here fits the disk shape reasonably well, its maximum brightness is about a magnitude higher than in the observed image.

We have explored a wide range of parameter space for the models, and we find that the match between well-mixed models and observations is less than ideal. If one makes the model disk more massive or makes the grains smaller (so that opacity in the near-IR is higher) to increase its self-absorption and decrease the maximum brightness, the width of the dark lane grows too large. On the other hand, if one makes the model disk less massive or the maximum grain size bigger, in order to make the disk less efficient at scattering stellar radiation, it is also less opaque and the maximum brightness becomes too high, because a larger fraction of direct stellar radiation can be transported through the disk. One plausible explanation for the discrepancy is dust settling to the midplane of the disk. In that case, the midplane dust contributes to the absorption of the
stellar radiation in the dark lane, but not much to the emission of the nebulosities, above and below the dark lane. The present models, which assume that dust and gas are well mixed, cannot self-consistently account for such an effect. Observations at millimeter wavelengths could provide a better mass estimate for the disk.

5. DISCUSSION

LkHα 263C appears to be a member of a young quadruple system in the MBM 12 association, along with LkHα 263A+B and LkHα 262. The possibility of a chance alignment of these four young stars—particularly in a hierarchical fashion—with a 20′ × 20′ region is extremely small considering the low stellar density of the association (0.002 arcmin⁻²). However, because the projected separation of ~4000 AU between LkHα 263 and LkHα 262 approaches the upper limit of stable binaries (see Duquennoy & Mayor 1991), the latter component may become unbound from the quadruple in the future. Nevertheless, LkHα 263C is the third edge-on disk found in a multiple system and the first in a possible quadruple system. Components LkHα 263A+B and LkHα 262 are also likely to harbor disks since they both show significant excess in the mid-IR (Jayawardhana et al. 2001). It is not yet clear whether the dust in LkHα 263A+B resides around one or both components or in a circumbinary configuration.

While a majority of T Tauri stars are binaries, higher order multiple systems appear to be relatively rare (Ghez et al. 1997 and references therein). The formation of multiple stellar systems is still poorly understood. Currently, the most promising mechanism appears to be fragmentation during the collapse of dense molecular cloud cores (Bodenheimer et al. 2000). High spatial resolution observations of pre–main-sequence multiple systems, like those presented here, help us determine the stellar and disk configurations of young objects and can lead to better constraints on models of multiple star formation and early evolution. The fact that the disk of LkHα 263C is clearly neither coplanar nor parallel with its orbital plane is a particularly useful test for such models.

We with to thank Kathy Roth, Francois Rigaut, Mark Chun, Olivier Guoyon, and Dan Potter for their assistance in obtaining the observations at the Gemini Observatory. We also thank Davy Kirkpatrick and the staff of the Keck Observatory for their assistance in the Keck observations. We are grateful to Javier Ballesteros for his help with the modeling.

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