ABSTRACT

We present observations of a circumstellar disk that is inclined close to edge-on around a young brown dwarf in the Taurus star-forming region. Using data obtained with SpeX at the NASA Infrared Telescope Facility, we find that the slope of the 0.8–2.5 μm spectrum of the brown dwarf 2MASS J04381486+2611399 cannot be reproduced with a photosphere reddened by normal extinction. Instead, the slope is consistent with scattered light, indicating that circumstellar material is occulting the brown dwarf. By combining the SpeX data with mid-infrared photometry and spectroscopy from the Spitzer Space Telescope and previously published millimeter data from Scholz and coworkers, we construct the spectral energy distribution (SED) for 2MASS J04381486+2611399 and model it in terms of a young brown dwarf surrounded by an irradiated accretion disk. The presence of both silicate absorption at 10 μm and silicate emission at 11 μm constrains the inclination of the disk to be ~70°, i.e., ~20° from edge-on. Additional evidence of the high inclination of this disk is provided by our detection of asymmetric bipolar extended emission surrounding 2MASS J04381486+2611399 in high-resolution optical images obtained with the Hubble Space Telescope. According to our modeling for the SED and images of this system, the disk contains a large inner hole that is indicative of a transition disk ($R_{\text{in}} \approx 58 R_{\odot} \approx 0.275$ AU) and is somewhat larger than expected from embryo ejection models ($R_{\text{out}} = 20–40$ AU vs. $R_{\text{out}} < 10–20$ AU).

Subject headings: accretion, accretion disks — planetary systems; protoplanetary disks — stars: formation — stars: low-mass, brown dwarfs — stars: pre-main-sequence

1. INTRODUCTION

Measurements of the properties of circumstellar accretion disks around young stars are important because they represent constraints on the initial conditions of planet formation. A unique set of measurements can be performed on a disk in the rare case in which it is seen close to edge-on. Because an edge-on disk occults the central star, scattered light from the disk surface dominates the total emergent flux at optical and near-infrared (IR) wavelengths, making it possible to spatially resolve the disk with high-resolution imaging (Burrows et al. 1996). At mid-IR wavelengths, the outer disk is seen in absorption against the star and inner disk, allowing spectroscopic measurements of the disk composition (Watson et al. 2004; Pontoppidan et al. 2005). The sample of edge-on disks discovered to date remains small. Some of the most notable examples are Orion 114-426 (McCaughran & O’Dell 1996), Haro 6-5B (Krist et al. 1998), HH 30 (Burrows et al. 1996), IRAS 04302+2247 (Lucas & Roche 1997; Padgett et al. 1999), DG Tau B (Padgett et al. 1999), OphE-MM3 and CRBR 2422.8-3423 (Brandner et al. 2000), HK Tau B (Stapelfeldt et al. 1998; Koaresko 1998), HV Tau C (Monin & Bouvier 2000), LKHo 263C (Jayawardhana et al. 2002; Chauvin et al. 2002), 2MASS J1628137–243139 (Grosso et al. 2003), and PDS 144 (Perrin et al. 2006). Additional young stars in Taurus exhibit dust lanes that may also trace edge-on disks (Hartmann et al. 1999; Padgett et al. 1999).

Because young stars with edge-on disks are seen only in scattered light at optical and near-IR wavelengths, they appear much fainter than unocculted young stars at a given spectral type. Recent spectroscopic surveys of nearby star-forming regions have identified a number of objects that are subluminous in this manner (Fernández & Comerón 2001; Luhan et al. 2003; Slesnick et al. 2004). One of these sources, 2MASS J04381486+2611399 in Taurus (hereafter 2M 0438+2611), appears to be a brown dwarf with a mass near 0.05 M$_\odot$ (Luhan 2004). This brown dwarf also exhibits anomalous near-IR colors and strong forbidden line emission, which are characteristics that are frequently observed in stars with edge-on disks. To definitively establish whether 2M 0438+2611 has an edge-on disk, we have observed it with near- and mid-IR spectroscopy and high-resolution optical imaging. In this paper, we present these new data (§ 2) and fit them with the predictions of accretion disk models to constrain the inclination and other physical properties of the disk around 2M 0438+2611 (§ 3).

2. OBSERVATIONS AND ANALYSIS

2.1. Near-Infrared Spectroscopy

To investigate the possibility that 2M 0438+2611 is seen in scattered light, we first obtained a low-resolution near-IR spectrum of it with SpeX (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF). These data were collected on the night of...
2512 do not exhibit excess emission from a disk. and to dwarf standards. Based on that comparison, the SpeX data for 2M 0444 + 2 cannot be reproduced by applying reddening to the standard. Bottom: The anomalous slope of 2M 0438+2611 is further illustrated by the ratio of the spectra of these two objects (solid line), which departs significantly from the constant ratio expected for normal reddening of a photosphere. The absence of significant residuals in this ratio near the steam bands confirms that the two objects have similar spectral types.

2004 November 12. They were reduced with the SpeXtool package (Cushing et al. 2004) and corrected for telluric absorption (Vacca et al. 2003). The final spectrum extends from 0.8 to 2.5 μm and exhibits a resolving power of R = 100.

For most of the young brown dwarfs that we have observed in previous studies (e.g., Luhman et al. 2006), the differences in the slopes of their 0.8–2.5 μm spectra are consistent with differences in extinction. However, this is not the case for 2M 0438+2611, which has an anomalous slope that differs significantly from those of other objects, regardless of any correction for extinction using standard reddening laws (Rieke & Lebofsky 1985; Cardelli et al. 1989). This behavior is illustrated in Figure 1, where we compare 2M 0438+2611 to a typical unreddened young brown dwarf with the same optical spectral type. The standard was artificially reddened according to the reddening law of Cardelli et al. (1989) to the point that it has the same relative fluxes at 0.8 and 2.5 μm as 2M 0438+2611. However, the shape of this reddened spectrum between 0.8 and 2.5 μm differs significantly from that of 2M 0438+2611. An alternative demonstration of this effect is shown in Figure 1 through the quotient of these two spectra, which departs from the constant value expected for normal reddening. Thus, reddening cannot explain the observed slope of 2M 0438+2611. Instead, relative to the flux at 0.8 μm, the spectrum of 2M 0438+2611 becomes redder more slowly with longer wavelengths than expected from standard extinction laws, which is consistent with the presence of (blue) scattered light in the spectrum. Meanwhile, the absence of significant residuals in the quotient of 2M 0438+2611 and the standard demonstrates the close match in the depths of the steam absorption bands, supporting the similarity in spectral types indicated by previous optical spectroscopy.

2.2. Mid-Infrared Spectroscopy

Photometry at 2 μm from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), at 3–8 μm from the Infrared Array Camera (IRAC; Fazio et al. 2004) aboard the Spitzer Space Telescope (Werner et al. 2004), and at 1.3 mm from the 30 m telescope at the Institut de Radio Astronomie Millimétrique (IRAM) have previously revealed excess emission in 2M 0438+2611 that is indicative of circumstellar dust (Luhman 2004; Luhman et al. 2006; Scholz et al. 2006). To better constrain the properties of this material, we obtained a mid-IR spectrum of 2M 0438+2611 on 2005 March 19 with the Spitzer Infrared Spectrograph (IRS; Houck et al. 2004) as a part of the Guaranteed Time Observations of the IRS instrument team. These observations (AOR 12705792) were performed with the short-wavelength, low-resolution module of IRS, providing data from 5.3 to 14 μm with a resolving power of R = 90. The spectrum was processed with the S14 pipeline at the Spitzer Science Center. The remaining reduction was performed with the methods that have been previously applied to IRS data for other low-mass members of Taurus (Furlan et al. 2005). We have also measured photometry at 24 μm for 2M 0438+2611 from archival images obtained with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). Using the methods described by Allen et al. (2007) we measured a flux of 62.5 ± 3.3 mJy from these MIPS data.

We present the spectra from SpeX and IRS and the photometry from 2MASS, IRAC, MIPS, and IRAM for 2M 0438+2611 in Figure 2. The IRAC and IRS data agree well with each other, while the 2MASS photometry and the SpeX data differ significantly in both color and flux level. The SpeX data are consistent with a smooth extension of the IRAC and IRS data, while the 2MASS measurements appear to be discontinuous from the latter. The IRAC and IRS observations were performed only 4 months after the SpeX observations, while the 2MASS data were obtained 6 years earlier. Thus, one explanation for the discrepancy in the 2MASS photometry relative to the other data is variability, which is plausible for any young star and is particularly likely for an object that is seen in scattered light because of changes in the geometry of the occulting material. Therefore, we exclude the 2MASS photometry for the purposes of modeling the spectral energy distribution (SED) of 2M 0438+2611 in § 3.

2.3. Optical Imaging

Because of the initial evidence indicating that the SED of 2M 0438+2611 might be dominated by scattered light at optical and...
near-IR wavelengths (Luhman 2004; § 2.1), we sought to detect spatially resolved scattered light through high-resolution broadband optical imaging with the Hubble Space Telescope (HST). In addition, given the presence of forbidden line emission in optical spectra of this brown dwarf (Luhman 2004), we performed narrowband imaging centered on [O i] at 6300 Å in an attempt to detect resolved line emission from a jet or an outflow. Using the Wide Field Planetary Camera (WFPC2) aboard HST, we obtained images of 2M 0438+2611 through the F675W, F791W, F850LP, and F631N filters on 2005 October 22. The target was placed near the center of the PC, which has a plate scale of 0.046″ pixel⁻¹. Two images were taken in each filter, each with exposure times of 160 s for F675W, F791W, and F850LP, and 300 s for F631N. Each pair of images at a given filter was combined to create a single image.

In the [O i] image, 2M 0438+2611 is unresolved and no extended emission is detected. Meanwhile, each of the three broadband images reveals both a point source and spatially resolved emission, as shown in Figure 4. The extended emission is elongated and reaches 0.4″–0.5″ from one side of the point source at a position angle of 245°. Analysis of these images with the point-spread function of WFPC2 indicates that a small amount (~0.1″) of extended emission is present on the opposite side of the point source as well.

3. DISK MODEL

3.1. Model Parameters

We have modeled the SED of 2M 0438+2611 in Figure 2 following the procedures from D’Alessio et al. (1998, 1999, 2001, 2006). In short, we solve the equations for the disk vertical structure, assuming it is an α-disk heated by viscous dissipation and by stellar irradiation. The relatively high flux at 1.3 mm of this object (Scholz et al. 2006) suggests the presence of grains that are larger than typical grains in the interstellar medium. At the same time, the presence of the 10 μm silicate band and the shape of the extinction of the stellar SED are indicative of small grains. Therefore, we have constructed a disk model in which a large fraction of the dust has settled in the midplane, growing to a maximum size of ~1 mm, while a small fraction of the dust remains in the upper layers in the form of small interstellar-like grains (D’Alessio et al. 2006). The dust is assumed to be segregated spheres of “astronomical” silicates and graphite with abundances and optical constants from Draine & Lee (1984) and Weingartner & Draine (2001), and a size distribution of $n(a) \sim a^{-3.5}$, where $a$ is the grain radius (Mathis et al. 1977). For the small grains in the upper layers, the minimum and maximum grain radii are $a_{\text{min}} = 0.0005$ μm and $a_{\text{max}} = 0.25$ μm. For the large grains at the disk midplane, we use $a_{\text{min}} = 0.0005$ μm and $a_{\text{max}} = 1$ mm. The dust–to–gas mass ratio of the small grains is parameterized in terms of $\epsilon$, which is the ratio normalized by the standard interstellar value of ~0.01. We have calculated models for $0.01 < \epsilon < 1$. The dust–to–gas mass ratio of the large grains at the midplane is calculated assuming that the total mass in grains is conserved at each radius.

In our model, the dusty disk is truncated at a radius $R_{\text{in}}$, where the inner wall of the disk receives radiation from the brown dwarf and accretion shocks at the stellar surface with a normal incidence. A natural explanation for a wall of this kind is that the silicates are sublimated inside $R_{\text{in}}$ (Dullemond et al. 2001; Muzerolle et al. 2004). In this case, the temperature at the inner edge of the disk is $T_{\text{wall}} = T(R_{\text{in}}) \sim 1400$ K. However, disks can be truncated at larger radii, corresponding to lower temperatures (i.e., transitional disks). Therefore, we have modeled the wall emission
following the procedures of D'Alessio et al. (2005), varying the
temperature of the optically thin dust in the wind from 300 to
1400 K. We have adopted an accretion rate of $3 \times 10^{-11} M_\odot$ yr$^{-1}$
for our disk model, which is similar to the value derived by
Muzerolle et al. (2005) for 2M 0438+2611 through modeling
of the profile of its H$_\alpha$ emission line.

Although the disk surface density, $\Sigma$, is not an input parameter
for our models, we are able to modify it through the viscosity pa-
rameter $\alpha$, since $\Sigma \sim (\dot{M}/\alpha)$ for an $\alpha$-disk. When fitting the milli-
meter flux, decreasing $\alpha$ (i.e., increasing $\Sigma$) has the effect of
decreasing the outer radius of the disk. After exploring models
for $10^{-6} \leq \alpha \leq 10^{-2}$, we find that the observed millimeter flux
constrains $\alpha$ to the low end of this range if the accretion rate in
the outer disk is the same as the accretion rate onto the brown
dwarf.$^{10}$ For a brown dwarf disk, $\alpha \leq 10^{-4}$ implies a viscous
timescale of $t_v \gtrsim 25$ Myr, which is too long to justify our assump-
tion of a steady disk with a constant accretion rate throughout
the disk. It is possible that the accretion rate increases with disk
radius, as in the disk model from Gammie (1996). A higher ac-
cretion rate in the outer disk would correspond to lower $\alpha$ and
shorter $t_v$. In a disk of this kind, material would accumulate in the
inner disk, perhaps in a dead zone. Exploring this possibility in
detail would require a disk model that includes a dead zone.

For the photosphere of 2M 0438+2611, we have adopted an
effective temperature of 2838 K (Luhman 2004). Because this
object is seen in scattered light at optical and near-IR wave-
lengths (Luhman 2004; § 2.1), its extinction cannot be mea-
sured from its colors. As a result, we cannot reliably measure its
luminosity with the normal method of applying an extinction cor-
tection to photometry in these bands. Therefore, we have per-
domed the disk calculations for a range of luminosities that
are typical of members of Taurus near the spectral type of
2M 0438+2611, namely $L_{\text{bol}} = 0.04, 0.06, 0.08$, and $0.1 L_\odot$. For
2M 0438+2611, we adopt a mass of $0.05 M_\odot$, which is the value
implied by its spectral type for a member of Taurus (Luhman
2004). As shown in Luhman (2004) and § 2.1, 2M 0444+2512
has the same optical and IR spectral types as 2M 0438+2611. In
addition, although it exhibits mid-IR excess emission that indi-
cates the presence of a disk (Luhman et al. 2006), 2M 0444+2512
does not show excess emission at wavelengths shortward of
2.5 $\mu$m in a comparison to SpeX data for diskless brown dwarfs
near the same spectral type (Luhman 2006). Therefore, we have
adopted the extinction-corrected SpeX data for 2M 0444+2512
described in § 2.1 to represent the 0.8–2.5 $\mu$m SED of the photo-
sphere of 2M 0438+2611. We assume that both 2M 0438+2611
and 2M 0444+2512 are at the average distance of members of
Taurus ($d = 140$ pc; Wichmann et al. 1998). We measured the
average colors between 2MASS $K_\text{s}$ and the IRAC bands (3.6,
4.5, 5.8, and 8.0 $\mu$m) for diskless late-type members of Taurus
(Hartmann et al. 2005; Luhman et al. 2006) and applied them to
the SpeX data for 2M 0444+2512 to extend the photospheric SED to 8.0 $\mu$m. The SED was extrapolated to wavelengths be-
yond 8.0 $\mu$m with a Rayleigh-Jeans distribution.

3.2. Best-Fit Model

A given portion of the observed SED provides constraints on
specific properties of the disk. We use the $K$-band flux to esti-
mate the optical depth to the brown dwarf, which in turn con-
strains the inclination, outer radius, and viscosity parameter
of the disk. The silicate feature near 10 $\mu$m is sensitive to both
the inclination and the presence of small grains in the upper layers
of the disk. The abundance of these small grains is constrained
by the 24 $\mu$m flux relative to the emission at shorter wavelengths.
The flux at 3–10 $\mu$m depends on the inner radius of the disk and
the stellar luminosity, while the millimeter flux is determined by
a combination of the outer radius and the surface density. In
this section, we discuss each of these constraints in detail for 2M
0438+2611 and present the resulting best-fit model for its disk.

The best fit to the flux at 3–10 $\mu$m is provided by a stellar lu-
ninosity of 0.06 $L_\odot$ (corresponding to $R_*/= 1.02 R_\odot$) and a ra-
dius of $R_\text{in} \approx 58 R_\star \approx 0.275$ AU for the wall, which corresponds
to a wall temperature of 400 K. For models with the wall placed
at the dust destruction radius, the predicted fluxes at 3–10 $\mu$m are
brighter than the observed values. Thus, our modeling indicates
that the disk is inwardly truncated. The inner disk of 2M 0438+
2611 shows the same physical properties as disks that have been
identified in the literature as “transitional disks,” and that have
been shown to have truncated optically thick disks at various dis-
tances from the central stars, from both SED modeling (Calvet
et al. 2002, 2005; D’Alessio et al. 2005; Muzerolle et al. 2006)
and millimeter interferometry (Hughes et al. 2007). Disks of this
kind are thought to harbor forming planets that are opening
gaps in the disk (Rice et al. 2003; Quillen et al. 2004). Photo-
evaporation is an alternative explanation for these disk gaps,
but it is unlikely for 2M 0438+2611 given the low ultraviolet
fluxes that are expected from a brown dwarf (Muzerolle et al.
2006).

For all reasonable choices of model parameters, the reddened
flux from the stellar photosphere should dominate the total emerg-
ent flux at $\sim 2–3$ $\mu$m. Combining the observed $K$-band flux and
the observed $K$-band flux produces a value of $\tau_{25, \mu m} \approx 1.3$ for
the optical depth to the photosphere.

The 10 $\mu$m silicate profile of 2M 0438+2611 is distinctive,
showing both absorption and emission components. This profile
tightly constrains the disk inclination because small angles pro-
duce only emission and large ones produce only absorption, as
illustrated for the face-on and edge-on disks around FM Tau and
DG Tau B in Figure 3 (Watson et al. 2004; Furlan et al. 2006).
For $i \sim 70^\circ$, the model predicts silicate emission from the disk
and silicate absorption from the highly extinguished wall that
combine to form absorption and emission features at 10 and 11 $\mu$m,
which closely matches the data, as shown in Figure 3. While mod-
eling IR and millimeter photometry for 2M 0438+2611, Scholz
et al. (2006) also used a high inclination angle of $i \approx 80^\circ$ for their
model of this disk. A high inclination was produced by their
model because 2M 0438+2611 is much fainter than the photo-
sphere of typical young brown dwarfs, so a highly inclined, ob-
scuring disk was needed to suppress the near- and mid-IR fluxes
of their adopted photospheric template to the observed levels.
Thus, their evidence for a high inclination disk was equivalent to
that presented by Luhman (2004), who showed that 2M 0438+
2611 is anomalously faint at near-IR wavelengths for its spec-
tral type and might be occulted by circumstellar material. The
distinctive silicate features in our IRS spectra (as well as the
extended emission in the WFC2 images) represent new evi-
dence of a highly inclined disk around 2M 0438+2611. Scholz
et al. (2006) suggested that the disk around 2M 0444+2512
also might have a high inclination. However, the slope of its
near-IR spectrum is consistent with a small amount of extinction
and a normal reddening law, and thus does not indicate the pres-
ence of scattered light. In addition, an unpublished IRS spectrum
of 2M 0444+2512 does not show the silicate absorption that is
seen in 2M 0438+2611 and other highly inclined disks (Fig. 3).

The flux at 24 $\mu$m is sensitive to the degree of dust settling in
the disk. We find that small grain abundances of $0.03 < \epsilon < 0.09$

$^{10}$ Disks around T Tauri stars have been modeled with $\alpha \sim 0.01$ (D’Alessio
et al. 1998).
in the upper layers of the disk are required to explain the observed 24 \text{$\mu$m} flux. For values of $\epsilon$ that are outside of this range, the predicted slope of the mid- and far-IR SED is smaller or larger than the observed one.

In Table 1 we summarize the models that provide the best fits to the SED of 2M 0438+2611 for five values of $\alpha$. The SEDs produced by these models are shown with the observed SED in Figure 2. These models reproduce the observed SED longward of 2 \text{$\mu$m} equally well, while the model for $\alpha = 10^{-4}$ provides a somewhat better match to the flux at shorter wavelengths. The disk radii of these models range from 5 to 200 AU. Thus, the SED alone does not provide a useful constraint on the outer radius of the disk.

To estimate the disk radius for 2M 0438+2611, we compare the images produced by each of our five models to the WFPC2 images in Figure 4. The WFPC2 data show a central peak surrounded by asymmetric bipolar emission. In comparison, the model images for $R_{\text{out}} = 5$ and 12 AU show a point source and no detectable extended emission, and the model for $R_{\text{out}} = 200$ AU produces too much extended emission. Meanwhile, the images from the models for $R_{\text{out}} = 20$ and 40 AU agree reasonably well with the WFPC2 images of 2M 0438+2611. The relative fluxes of the two lobes of emission are better matched by the model for $R_{\text{out}} = 20$ AU, while the length of the extended emission is better matched by $R_{\text{out}} = 40$ AU. Thus, the WFPC2 images constrain the disk radius to be $R_{\text{out}} = 20–40$ AU and confirm the high inclination that is implied by the SED analysis. In addition, given that the model images are formed by stellar light scattered at the disk surface and extinguished by the outer disk, the agreement between the optical SED and the predicted scattered-light spectrum and flux level (Fig. 2) is further evidence supporting our estimate of the depletion factor of small grains in the upper disk layers.

4. CONCLUSIONS

The young brown dwarf 2M 0438+2611 exhibits several characteristics that are often observed in stars with edge-on disks, such as unusually faint near-IR fluxes for its spectral type, strong emission in forbidden transitions, and anomalous near-IR colors (Luhman 2004). Through observations presented in this paper, we have confirmed that 2M 0438+2611 is occulted by a highly inclined disk. This new evidence is summarized as follows.

1. Based on a comparison to other young brown dwarfs, the slope of the 0.8–2.5 \text{$\mu$m} spectrum of 2M 0438+2611 cannot be explained as a photosphere reddened by a standard extinction law and instead is consistent with scattered light, which suggests that the brown dwarf is occulted by circumstellar material.

2. The presence of silicate absorption at $\sim$10 \text{$\mu$m} and silicate emission at $\sim$11 \text{$\mu$m} constrains the disk inclination angle to be near $\sim$70° (i.e., $\sim$20° from edge-on) because higher or lower inclinations would produce only absorption or emission, respectively.

3. We detect asymmetric bipolar emission in WFPC2 images of 2M 0438+2611, which is consistent with simulated scattered-light images produced by our model of a highly inclined disk around this brown dwarf.

| $\alpha$ (10$^{-4}$) | $R_{\text{out}}$ (AU) | $M_{\text{disk}}$ ($M_{\odot}$) | $i$ (deg) | $\epsilon$ |
|----------------------|-----------------------|-------------------------------|------------|----------|
| 0.05                 | 5                     | 700                           | 68         | 0.04     |
| 0.5                  | 12                    | 140                           | 70         | 0.03     |
| 0.8                  | 20                    | 130                           | 71         | 0.03     |
| 1                    | 40                    | 190                           | 67         | 0.09     |
| 2                    | 200                   | 340                           | 70         | 0.09     |
In addition to its inclination, we have been able to constrain several other properties of the disk around 2M 0438+2611 through modeling of its SED and high-resolution images. These constraints are made possible by the unusual wealth of data available for this disk, although achieving a self-consistent model that simultaneously reproduces those data has proved to be quite challenging. In our best-fit models, the disk has an inclination of $i \approx 70^\circ$, an inner radius of $58R_\star \approx 0.275$ AU, an outer radius of 20–40 AU, a total mass of 100–200 $M_\oplus$, and an abundance of small grains in its upper layers of $0.03 \lesssim \epsilon \lesssim 0.09$, indicating a large

![WFPC2 images of 2M 0438+2611 (top row) and simulated images produced by the disk models that fit the SED in Fig. 2 (bottom five rows). In the model images, the disk is close to edge-on ($i \approx 70^\circ$) and is aligned close to north-south. Thus, the extended emission in the horizontal direction is above and below the disk. For each image, the intensity is displayed on a logarithmic scale and the size is $1.5'' \times 1.5''$.](image)
degree of settling to the midplane. Our estimate of the inner radius suggests the presence of a large inner hole, which is a characteristic of transitional disks (Calvet et al. 2002, 2005; D’Alessio et al. 2005; Muzerolle et al. 2006). Meanwhile, the outer radius of the disk around 2M 0438+2611 is somewhat larger than expected from models of embryo ejection ($R_{\text{out}} < 10 – 20 \text{ AU}$; Bate et al. 2003).

We acknowledge support from grant GO-10511 from the Space Telescope Science Institute and grant AST 05-44588 from the National Science Foundation (K. L.), grants from CONACyT and PAPIIT/DGAPA, México (P. D.), and NASA grants NAG5-9670 and NAG5-13210 (N. C. and L. H.).

REFERENCES

Allen, P. R., et al. 2007, ApJ, 655, 1095
Bate, M. R., Bonnell, I. A., & Bromm, V. 2003, MNRAS, 339, 577
Brandner, W., et al. 2000, A&A, 364, L13
Burrows, C. J., et al. 1996, ApJ, 473, 437
Calvet, N., D’Alessio, P., Hartmann, L., Wilner, D., Walsh, A., & Sitko, M. 2002, ApJ, 568, 1008
Calvet, N., et al. 2005, ApJ, 630, L185
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chauvin, G., et al. 2002, A&A, 364, L13
Burrows, C. J., et al. 1996, ApJ, 473, 437
Calvet, N., D’Alessio, P., Hartmann, L., Wilner, D., Walsh, A., & Sitko, M. 2002, ApJ, 568, 1008
Calvet, N., et al. 2005, ApJ, 630, L185
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chauvin, G., et al. 2002, A&A, 394, 949
Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2004, PASP, 116, 362
D’Alessio, P., Calvet, N., & Hartmann, L. 2001, ApJ, 553, 321
D’Alessio, P., Calvet, N., Hartmann, L., Franco-Hernández, R., & Servín, H. 2006, ApJ, 638, 314
D’Alessio, P., Calvet, N., Hartmann, L., Lizano, S., & Cantó, J. 1999, ApJ, 527, 893
D’Alessio, P., Canto, J., Calvet, N., & Lizano, S. 1998, ApJ, 500, 411
D’Alessio, P., et al. 2005, ApJ, 621, 461
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957
Fazio, G. G., et al. 2004, ApJS, 154, 10
Fernández, M., & Comerón, F. 2001, A&A, 380, 264
Furlan, E., et al. 2005, ApJ, 621, L129
———. 2006, ApJS, 165, 568
Gammie, C. F. 1996, ApJ, 457, 355
Grosso, N., Alves, J., Wood, K., Neuhauser, R., Montmerle, T., & Bjorkman, J. E. 2003, ApJ, 586, 296
Hartmann, L., Calvet, N., Allen, L., Chen, H., & Jayawardhana, R. 1999, AJ, 118, 1784
Hartmann, L., et al. 2005, ApJ, 629, 881
Houck, J. R., et al. 2004, ApJS, 154, 18
Hughes, A. M., et al. 2007, ApJ, 664, 536
Jayawardhana, R., Luhman, K. L., D’Alessio, P., & Stauffer, J. R. 2002, ApJ, 571, L51
Koresko, C. D. 1998, ApJ, 507, L145
Krist, J. E., et al. 1998, ApJ, 501, 841
 Lucas, P. W., & Roche, P. F. 1997, MNRAS, 286, 895
Luhman, K. L. 2004, ApJ, 617, 1216
———. 2006, ApJ, 645, 676
Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093
Luhman, K. L., Whitney, B. A., Meade, M. R., Babler, B. L., Indebetouw, R., Bracker, S., & Churchwell, E. B. 2006, ApJ, 647, 1180
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
McCaughrean, M. J., & O’Dell, R. C. 1996, AJ, 111, 1977
Monin, J.-L., & Bouvier, J. 2000, A&A, 356, L75
Muzerolle, J., D’Alessio, P., Calvet, N., & Hartmann, L. 2004, ApJ, 617, 406
Muzerolle, J., Luhman, K. L., Briceño, C., Hartmann, L., & Calvet, N. 2005, ApJ, 625, 906
Muzerolle, J., et al. 2006, ApJ, 643, 1003
Padgett, D. L., et al. 1999, AJ, 117, 1490
Perin, M. D., Duchêne, G., Kalas, P., & Graham, J. R. 2006, ApJ, 645, 1272
Pontoppidan, K. M., et al. 2005, ApJ, 622, 463
Quillen, A. C., Blackman, E. G., Frank, A., & Varnière, P. 2004, ApJ, 612, L137
Rayner, J. T., et al. 2003, PASP, 115, 362
Rice, W. K. M., Wood, K., Armitage, P. J., Whitney, B. A., & Bjorkman, J. E. 2003, MNRAS, 342, 79
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Rieke, G. H., et al. 2004, ApJS, 154, 25
Scholz, A., Jayawardhana, R., & Wood, K. 2006, ApJ, 645, 1498
Skrutskie, M., et al. 2006, AJ, 131, 1163
Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, ApJ, 610, 1045
Stapelfeldt, K. R., et al. 1998, ApJ, 502, L65
Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, PASP, 115, 389
Watson, D. M., et al. 2004, ApJS, 154, 391
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Werner, M. W., et al. 2004, ApJS, 154, 1
Wichmann, R., Bastian, U., Krautter, J., Jankovics, I., & Ruciński, S. M. 1998, MNRAS, 301, L39