# A young protoplanetary disk in the Bok globule CB 26?

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## ABSTRACT

We present sub-arcsecond resolution millimeter-wave images of a circumstellar disk in the Bok globule CB 26. The presence of an edge-on disk is confirmed by the dust continuum morphology and the velocity field of $^{13}$CO emission, which displays a Keplerian rotation pattern about an axis perpendicular to the long axis of the dust emission. We deduce a mass $\sim 0.3 \, \mathrm{M_\odot}$ for the obscured central star. The disk is optically thick at mm wavelengths inside 120 AU, has a symmetric 20° warp beyond 120 AU, an outer radius of $\sim 200$ AU, and a mass of at least $0.1 \, \mathrm{M_\odot}$. We suggest that the CB 26 system is in an intermediate stage between deeply embedded protostellar accretion disks and the more evolved, perhaps protoplanetary, disks around T Tauri stars.

*Subject headings:* circumstellar matter — dust, extinction — ISM: globules — planetary systems: protoplanetary disks — stars: formation

## 1. Introduction

CB 26 (L 1439) is a small cometary-shaped Bok globule located $\sim 10°$ north of the Taurus/Auriga dark cloud. Launhardt & Henning (1997) suggested a distance of 300 pc. From a re-examination of the larger-scale velocity structure (Ungerechts & Thaddeus 1987), we believe it is part of the Taurus/Auriga complex at 140 pc. Single-dish submm images at $10''$ resolution show strong unresolved dust continuum emission at the south-west rim of the globule, surrounded by a thin asymmetric envelope with a well-ordered magnetic field directed along PA $\sim 25°$ (Henning et al. 2001). A small bipolar near-infrared (NIR) nebula bisected by a dark extinction lane is associated with the millimeter emission. The sub-arcsecond resolution NIR polarization pattern is consistent with the presence of an almost edge-on circumstellar disk elongated along the extinction lane at PA $\sim 60°$ and a thin envelope (Stecklum et al. 2001). The spectral energy distribution indicates a low-mass, $\geq 0.5 \, \mathrm{L_\odot}$ pre-main sequence (PMS) star surrounded by a disk and an envelope (Stecklum et al. 2001), i.e., a Class I object (Adams, Lada, & Shu 1987; Kenyon & Hartmann 1995).

## 2. Observations and data reduction

CB 26 was observed with the Owens Valley Radio Observatory (OVRO) millimeter-wave array between January and December 2000. Three configurations of the six 10.4 m antennas provided baselines in the range $6 - 180 \, \mathrm{k}\lambda$ at 2.7 mm (110 GHz) and $12 - 400 \, \mathrm{k}\lambda$ at 1.3 mm (232 GHz). Average SSB system temperatures of the SIS receivers were $300 - 400$ K at 110 GHz and $300 - 600$ K at 236 GHz. The digital correlator was centered on the $^{13}$CO(1–0) line at 110.2 GHz, adopting the systemic velocity of CB 26, $v_{\mathrm{LSR}} = 5.5 \, \mathrm{km \, s^{-1}}$; spectral resolution and bandwidth were $0.17 \, \mathrm{km \, s^{-1}}$ and $5 \, \mathrm{km \, s^{-1}}$, respectively. Continuum emission at 1.3 and 2.7 mm was observed simultaneously in 2 GHz-wide bands, except in the highest-resolution configuration, where the 4 GHz wide-band capability of new 1 mm receivers was used. Amplitude and phase calibration relied on frequent observations of a nearby quasar, resulting in absolute position uncertainty of $0''.2$. Flux densities are based on observations of Uranus and Neptune, with resulting uncertainties of 20%. The raw data were calibrated and edited using the MMA software package (Scoville et al. 1993). Mapping and data analysis used the MIRIAD tool-

box (Sault, Theuben, & Wright 1995). We also applied maximum entropy deconvolution (MEM) to the data and obtained images which are very similar to those obtained by standard cleaning.

## 3. Results

In Fig. 1, our dust continuum images of CB 26 show a source elongated along PA = $60 \pm 5°$. At 2.7 mm, the projected length derived from the distribution of clean components is 230±30 AU. The minor axis is unresolved and there is no hint of an envelope. By contrast, the 1.3 mm images show a narrow central structure of length 400±40 AU and a small envelope of size 220 AU × 280 AU. The scale height $h$ of the central structure remains unresolved, i.e., $h \le 20$ AU. Beyond radii of 120 AU, an almost symmetric 20° warp is apparent in Fig. 1d. Total continuum flux densities are 22±4 mJy and 150±30 mJy at 2.7 and 1.3 mm, respectively. Thus, we recover completely the 1.3 mm flux of the unresolved component as measured with the IRAM 30-m telescope, 160 mJy (Launhardt & Henning 1997). From our maps, we calculate that about 50 mJy arises in the envelope and 100 mJy in the narrow central structure. Of this 100 mJy, about 75 mJy derives from the inner 230 AU where the 3 mm emission arises.

In Fig. 2, the 1.3 mm continuum MEM image is overlaid on a map of the NIR reflection nebula. Within the NIR astrometric uncertainties, 0″5, the dust emission coincides with the extinction lane and with the location and orientation of the disk postulated by Stecklum et al. (2001). Our kinematic data support the disk hypothesis. As illustrated in Fig. 3a, strong $^{13}$CO(1–0) emission ($T^*_R \sim 20$ K) arises mainly from the outer parts of the disk, suggesting optically thick emission. In Fig. 3b, the $^{13}$CO line is clearly double-peaked, with blue-shifted emission concentrated to the north-east and red-shifted to the southwest. The velocity structure indicates a rotation axis perpendicular to the projected plane of the disk. At the systemic velocity, $v_{LSR} = 5.5$ km s$^{-1}$, gas emission appears to be self-absorbed, probably due to the extended outer envelope.

## 4. Discussion

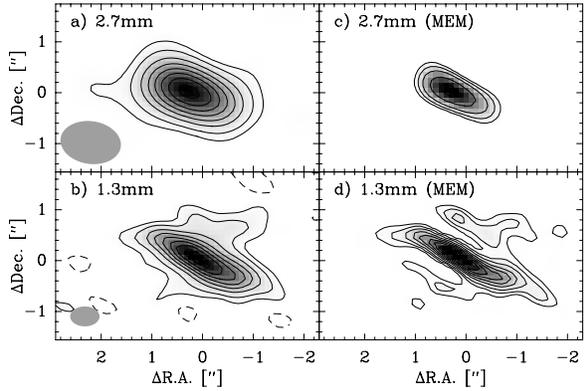Our millimeter interferometric observations of thermal dust continuum and $^{13}$CO line emission



Fig. 1.— Dust continuum emission from CB 26 (R.A.=04:59:50.74, DEC=+52:04:43.8, J2000): 1a) and b) Cleaned and restored 2.7 and 1.3mm maps. Contour levels are at -2, 2, 4, 7 ... 22 × 1$\sigma$ rms where $\sigma$ = 0.7 mJy/beam at 2.7mm and 1.3 mJy/beam at 1.3 mm. Beam sizes are shown as grey ovals (1″2×0″84 at 2.7mm and 0″58×0″39 at 1.3mm). c) and d) Deconvolved maps derived using the maximum entropy algorithm (MEM).
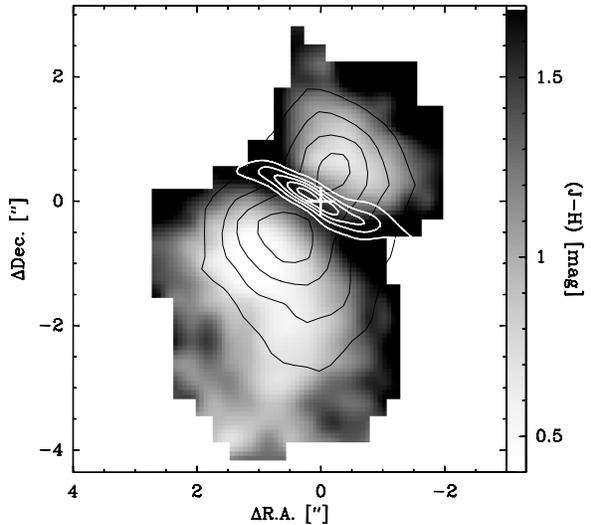


Fig. 2.— MEM image of the 1.3 mm dust emission (solid white contours at 4, 11, 18, 25, and 32 mJy/arcsec$^2$) overlaid on a J − H color map of the bipolar NIR reflection nebula. Black contours show the nebula K-band emission. The white cross denotes the presumed location of the illuminating star (from Stecklum et al. 2001).
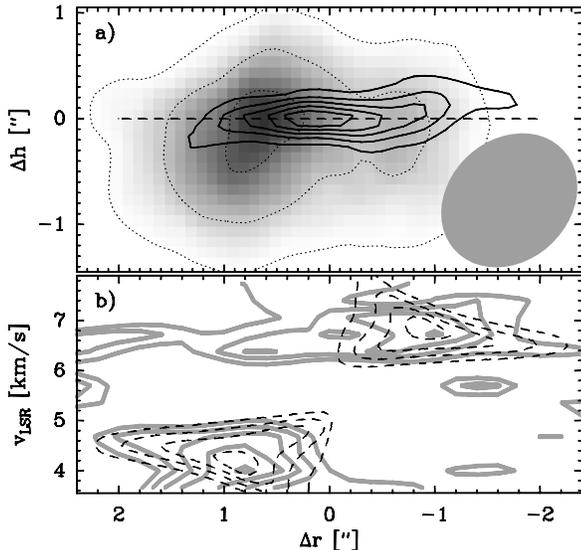
Fig. 3.— a) Integrated $^{13}$CO(1–0) emission from CB 26 in grey-scale (dotted contours at 8, 13.5, 19 K km s$^{-1}$) with 1.3 mm dust continuum contours overlaid. A dashed line represents the plane of the disk. The CO beam size is shown as grey ellipse. b) Position-velocity diagram along the disk major axis. Thick contours at 27, 45, 63, 81, 99% of the maximum intensity show the observed velocity field. The expected emission from a Keplerian disk around a 0.35 M$_\odot$ star is represented by dashed contours (see text).

from CB 26 confirm the presence of an edge-on circumstellar disk as postulated by Stecklum et al. (2001). The disk has a diameter of about 400 AU and an as yet unexplained warp beyond radii of 120 AU. This could be due to an undetected wide companion star with an inclined orbit.

The continuum fluxes lead to an average 1.3-3 mm dust emission spectral index $\alpha$ for the inner $R < 115$ AU of the disk of 1.7±0.2, where flux $S_\nu \propto \nu^\alpha$. Since $\alpha = 2$ for a blackbody in the Rayleigh-Jeans limit, emission from the inner disk must be very optically thick, making it difficult to constrain the mass. Beyond 120 AU, no 3 mm emission is detectable and $\alpha \geq 2.7\pm0.3$, suggesting optically thin emission. The transition between optically thick and optically thin emission occurs approximately at the radius where a warp appears, $\sim 120$ AU. Thus the outer disk may be disturbed and inflated, and flared T Tauri star

(TTS) disk models may no longer apply. Nevertheless we derived a lower limit to the disk mass by comparing the 1.3 and 2.7 mm continuum emission to spatially resolved radiative transfer calculations of different heuristic 'typical' TTS disk models characterized by temperature profiles, $T_d \propto r^{-q}$, with $q = 0.5-0.75$, surface density profiles, $\Sigma \propto r^{-p}$, with $p = 1.0-1.5$, and disk flaring, $H \propto r^z$, with $z = 0-1.5$ (e.g., Adams et al. 1987; Kenyon & Hartmann 1987). An interstellar gas-to-dust mass ratio of 100 and typical disk dust opacity $\kappa_{1.3} = 2 \, cm^2 \, g^{-1}$ with $\kappa \propto \nu^\beta$ and $\beta = 1$ were assumed (cf. Beckwith et al. 1990). All models suggest disk masses of at least 0.1 M$_\odot$. Due to the high optical depths of the $^{13}$CO line, self-absorption, and possible depletion (cf. Thi et al. 2001), an independent mass estimate from the molecular line emission is unobtainable.

The envelope detected in the 1.3 mm images (Figs. 1b, 1d) is probably associated with an outflow or disk wind. Assuming optically thin emission at temperature 30 K and $\kappa_{1.3} = 1 \pm 0.5 \, cm^2 \, g^{-1}$, a fairly typical value for dense protostellar cores (cf. Ossenkopf & Henning 1994), we derive $M_H(env) = 0.01\pm0.003$ M$_\odot$. For a cylindrical morphology (cf. Figs. 1b, 1d, and Sect. 3), we infer an average density $\langle n_H \rangle \sim 3\,10^8 \, cm^{-3}$, column density $N_H \sim 5\,10^{23} \, cm^{-2}$, and corresponding visual extinction $A_V \sim 300$ mag, implying that back-warming from the envelope has to be considered in the energy balance of the disk (cf. Butner, Natta, & Evans 1994). The total mass of the more extended ($\sim 3000$ AU diameter) asymmetric envelope seen in single-dish maps is $0.1 \pm 0.05$ M$_\odot$ (Henning et al. 2001). This may be a remnant of the globule core from which the system formed.

The velocity structure of $^{13}$CO can be modeled by Keplerian rotation when the high optical depth of the inner disk and self-absorption due to an extended envelope are taken into account, yielding a mass of the central star of 0.35±0.1 M$_\odot$ (cf. Fig. 3b). However, since the disk mass ($\geq 0.1$ M$_\odot$) is comparable to the inferred mass of the central star, self-gravitation may be important in the outer disk (cf. Bertin & Lodato 1999). The outer rotation curve would then be flatter than in the pure Keplerian case, and the mass of the central star concomitantly lower, perhaps only 0.25 M$_\odot$. The $^{13}$CO line strength suggests a gas-rich disk with kinetic temperature $\geq 20$ K outside $R \sim 100$ AU. An upper

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limit to the turbulent velocity dispersion in the disk is $0.3\,\mathrm{km\,s^{-1}}$.

PMS evolutionary tracks indicate an age of $7 \pm 2 \times 10^5\,\mathrm{yr}$ for a $0.3\,\mathrm{M_\odot}$ star with $L = 0.5\,\mathrm{L_\odot}$ (D'Antona & Mazzitelli 1994). Due to the anisotropic radiation field caused by the optically thick edge-on disk, $0.5\,\mathrm{L_\odot}$ may be only a lower limit to the bolometric luminosity of the central star (see Men'shchikov & Henning 1999). But, for such a massive disk, the intrinsic viscous luminosity could also contribute. Overall, the properties of the CB 26 system are consistent with its being younger than classical TTSs (ages $10^6 - -10^7\,\mathrm{yr}$). There is no dense, centrally peaked cloud core with evidence of collapse, and no prominent molecular outflow, indicating that the main accretion phase, assumed to last a few times $10^4\,\mathrm{yr}$ (e.g., André, Ward-Thompson, & Barsony 2000), has ended. However, the disk mass is close to the theoretical gravitationally unstable limit, $0.3\,\mathrm{M_*}$, so that the envelope may still be accreting at low rates onto the disk (see Hollenbach, Yorke, & Johnstone 2000, and references therein). Indeed, Fig. 3b shows some 'forbidden' red-shifted emission from the blue side of the disk which may be due to infall.

We conclude that the CB 26 disk surrounds a PMS M-type star with age $\sim 10^5\,\mathrm{yr}$. This represents an intermediate stage between such deeply embedded protostellar accretion disks as L 1551 IRS5 (e.g., Butner et al. 1994), and the more evolved, perhaps protoplanetary, disks around classical TTSs, which may be the reservoirs for material for planet formation.

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