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**Citation**
Patel, Nimesh A., Salvador Curiel, T. K. Sridharan, Qizhou Zhang, Todd R. Hunter, Paul T. P. Ho, José M. Torrelles, James M. Moran, José F. Gómez, and Guillem Anglada. 2005. "A Disk of Dust and Molecular Gas Around a High-Mass Protostar." Nature 437 (7055) (September 1): 109–111. doi:10.1038/nature04011.

**Published Version**
10.1038/nature04011

# A DISK OF DUST AND MOLECULAR GAS AROUND A HIGH-MASS PROTOSTAR

**N. A. Patel[1], S. Curiel[1,2], T. K. Sridharan[1], Q. Zhang[1], T. R. Hunter[1]**

**P.T.P. Ho[1], J. M. Torrelles[3], J. M. Moran[1], J. F. Gómez[4], G. Anglada[5]**

**Received** ______________; **accepted** ______________

[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

[2]Instituto de Astronomia, UNAM, Unidad Morelia, Mexico

[3]Consejo Superior de Investigaciones Científicas-IEEC, Spain. On sabbatical leave at the UK Astronomy Technology Centre, Royal Observatory Edinburgh

[4]Laboratorio de Astrofisica Espacial y Fisica Fundamental, INTA, Madrid, Spain

[5]Instituto de Astrofisica de Andalucia, CSIC, Granada, Spain

**The processes leading to the birth of low-mass stars such as our Sun have been well studied[1], but the formation of high-mass ($> 8\times$ Sun's mass $M_\odot$) stars has heretofore remained poorly understood[2]. Recent observational studies suggest that high-mass stars may form in essentially the same way as low-mass stars, namely via an accretion process[3], instead of via merging of several low-mass ($< 8M_\odot$) stars[4]. However, there is as yet no conclusive evidence[5,6]. Here, we report the discovery of a flattened disk-like structure observed at submillimeter wavelengths, centered on a massive 15 $M_\odot$ protostar in the Cepheus-A region. The disk, with a radius of about 330 astronomical units (AU) and a mass of 1 to 8 $M_\odot$, is detected in dust continuum as well as in molecular line emission. Its perpendicular orientation to, and spatial coincidence with the central embedded powerful bipolar radio jet, provides the best evidence yet that massive stars form via disk accretion in direct analogy to the formation of low-mass stars.**

Previously reported disk-like structures associated with high-mass stars, which are more than twice as far away as low-mass stars, have typical sizes of several thousands of AU. Furthermore, in such sources, the presence of thermal jets at scales of a few $\times10^2$AU has not been demonstrated, in part due to the lack of sufficient angular resolution. Consequently, it has not been possible to identify and isolate a good example of a high-mass protostar-disk-jet system[7,8,9]. The recently reported massive disk in M17-S01 (ref. 5), based on near-infrared observations of the disk in silhouette against the bright background light of the ionized region and in emission lines of carbon monoxide (CO), has subsequently been shown to be actually a much lower mass disk (0.09 $M_\odot$; ref. 6). In the former study[5], uncertainty resulted from (1) insufficient angular resolution ($8''$), (2) observations of molecular species that are most likely optically thick and a tracer of low-density gas (CO and its isotopes, $^{13}CO$ and $C^{18}O$), and (3) the absence of an independent means to infer the presence of a high-mass protostar such as bright radio continuum emission and/or luminous water maser sources.

Cepheus-A is a well studied high-mass star-forming region in the Cepheus OB3 complex[10,11]. The bolometric luminosity of this high-mass star-forming region is about $2.5\times10^4 L_\odot$ (ref. 12). Half of this luminosity is attributed to the HW2 object, the brightest radio continuum source in the field, that is considered to be a B0.5 spectral type protostar of 15 $M_\odot$ (refs. 13,14,15,16) and is the most likely exciting source of a powerful extended bipolar molecular outflow[17,18]. The radio continuum flux density of about 40 mJy at 1.3 cm wavelength[16] would correspond to a flux density of about 0.8 Jy if the source were at the distance of a typical low-mass star-forming region such as the Taurus molecular cloud (160 pc). This would be about 100 times brighter than typical low-mass protostars at that distance. Also associated with HW2 is a "biconical thermal radio jet" at the size scale of $\simeq 1''$ ($\simeq$725 AU), with the ionized gas exhibiting proper motions with velocities $\geq$ 500 km $s^{-1}$ along the axis of the jet[14,19,20]. In addition, we estimate that the luminosity of the masers associated with HW2(ref. 21) is $L(H_2O) \geq 3\times10^{-6}$ $L_\odot$, which is $\sim 10^3$ to $10^5$ times more luminous than water masers associated with low-mass stars (ref. 22). These comparisons strongly imply that HW2 is a high-mass protostar.

Our new sub-arcsecond angular resolution Submillimeter Array (SMA)[23] observations toward HW2 have far superior spatial resolution and sensitivity to dust emission, when compared to existing submillimeter observations made with single-dish telescopes or interferometric observations made at millimeter and centimeter wavelengths. This allowed us to directly image for the first time the compact circumstellar disk surrounding HW2 at the scale of a few hundred AU, and to define its physical properties. Figure 1 shows an overlay of the dust continuum emission at 327 GHz and the integrated intensity in the $CH_3CN$ J=18-17 line emission. The dust continuum emission was imaged by selecting spectrometer channels free of line emission. The deconvolved source radius is 330 AU ($0\farcs45$) in dust continuum emission, and 580 AU ($0\farcs8$) in $CH_3CN$ line emission. The integrated flux density from the dust emission is 2.0 Jy $\pm$ 0.1 Jy. The Gaussian-fitted positions of the dust and $CH_3CN$ emission peaks agree well to within a tenth of an arcsecond. The sizes, orientations and other characteristics are summarized in Table 1. By examining the visibility amplitudes as a function of baseline distance, we have confirmed that this flattened structure is well resolved along its major axis and partially resolved along its minor axis. The free-free continuum emission from the thermal jet at 1.3 and 3.6 cm wavelengths, observed with the Very Large Array (VLA), is also shown in Fig. 1. The 1.3 cm wavelength continuum emission traces the inner part of the jet, with the protostellar source most likely at its geometric center[16,19]. The position angle of the thermal jet at both 1.3 and 3.6 cm wavelengths is $\sim 45^o$. A large-scale extended ($\sim 1'$) bipolar outflow mapped in $HCO^+$ J=1-0 emission is centered at the position of HW2 (ref. 17) and has the same orientation as the much smaller scale centimeter wavelength continuum jet. The size and morphology of the dust and gas emission are in good agreement with each other and the elongation in both these emissions is seen to be nearly perpendicular to, and peaking on the biconical circumstellar thermal jet. This strongly supports the disk interpretation for the flattened structure seen in the dust and $CH_3CN$ emission. Based on these observations of the jet and outflow at various wavelengths, the existence of such a disk might be expected, since outflows in low mass stars are in fact launched from the inner portions of the rotating disks according to theoretical models (e.g., ref. 26). Although these models are for low-mass stars, our observational results suggest that outflows in high-mass stars may be produced in a similar fashion.

Figure 2 shows a position-velocity diagram along the major axis of the elongated emission seen in the $CH_3CN$ lines. From this diagram we see a velocity-gradient of $\simeq$6 km $s^{-1}$ over $0\farcs5$ (considering the largest velocity shift from the central position). We interpret this velocity gradient to be due to gravitationally bound rotational motion. The dynamical mass enclosed within a radius r with rotational velocity $v_r$ is given by $v_r^2 r/G$, where $G$ is the gravitational constant. The observed velocity (along the line-of-sight) is $v = v_r\sin(\mathrm{i})$, where i is the inclination angle of the disk axis with respect to the line-of-sight. From the mean value of the observed aspect ratio of gas and dust disk as listed in table 1, (i.e., assuming a circular disk) we estimate the inclination angle to be $\simeq 62^o$, and therefore a binding mass of $19\pm5$ $M_\odot$. This implies that the observed motions can be bound by the central high-mass protostar. In addition, from the line ratios of the $CH_3CN$ K components we can estimate the temperature of the gas[24]. We assume optically thin emission and a single value of temperature along the line-of-sight. From the ratios of the peak intensities of the K=3 and K=2 components, we find that the temperature varies along the major axis of the disk from ∼25 K to ∼75 K, with the northwest part of the disk relatively cooler and the southeast and central parts of the disk relatively hotter. The line width also appears to be greater at the latter positions. With the present angular resolution we are unable to map in detail the temperature and kinematics of the gas in the disk but we can make rough estimates of its mass. If we assume that the dust is optically thin, we can estimate the gas mass of the disk[27] assuming the gas-to-dust ratio of 100, gas temperature of 50 K (from analysis of methyl cyanide lines) and the measured 900 $\mu$m continuum flux density of 2.0 Jy. We also need to know the grain emissivity spectral-index $\beta$ for the dust emission. We obtain a mass estimate for the gas disk to be 1 $M_\odot$ for $\beta = 1$ (ref. 28) and 8 $M_\odot$ for $\beta = 2$ (ref. 29). Some of this mass could be in a rotationally flattened infalling envelope instead of the disk but we note that the observed size of the disk in HW2 is in good agreement with the range of $\simeq$ 400 to 600 AU for the centrifugal radius (the radius where disk formation is expected to occur) derived from a recent fitting of flattened infalling envelope models to the observed spectral energy distribution of high-mass protostars[30]. All these results support theoretical models of high-mass star-formation via an accretion process occurring in a disk around the protostar, accompanied by a bipolar outflow (much like low-mass stars), rather than by models that require merging of several low-mass stars.

Table 1. Characteristics of Cepheus-A HW2 dust continuum and $CH_3CN$ emission

| | Total flux density | major axis (") | minor axis (") | P. A. ($^o$) | $\Delta\alpha('')$ | $\Delta\delta('')$ |
|---|---|---|---|---|---|---|
| Continuum | 2.0 ± 0.1 Jy | 0.9 | 0.5 | -59.2±0.6 | -0.07 | 0.55 |
| $CH_3CN$ | 122 Jy km $s^{-1}$ | 1.6 | 0.6 | -56.2±0.2 | -0.04 | 0.58 |

Note. — Deconvolved Gaussian fitted model parameters for the Cepheus-A HW2 disk structure seen in continuum and $CH_3CN$ emission at 330 GHz (J=18- 17, K=0,1,2,3). The last two columns are the positions of the peaks with respect to $\alpha(2000) = 22^h56^m17.^s970, \delta(2000) = +62^o01'48.992''$. The uncertainties in the sizes and positions are $\sim 0.''1$.

## REFERENCES


1. Lada, C. J. & Shu. F. H. The formation of sunlike stars. *Science* **248**, 564-572 (1990).

2. Stahler, S. W., Palla, F. & Ho, P.T.P. in Protostars and Planets IV (eds Mannings, V., Boss, A. P. and Russell, S.) 327-351 (Univ. of Arizona Press, Tucson, 2000).

3. McKee, C. & Tan, J. The formation of massive stars from turbulent cores. *Astrophys. J.* **585**, 850-871 (2003).

4. Bonnell, I. A. & Bate, M. R. Accretion in stellar clusters and the collisional formation of massive stars. *Mon. Not. R. Astron. Soc.* **336**, 659-669 (2002).

5. Chini, R., Hoffmeister, V., Kimeswenger, S., Nielblock, M., Nurnberger, D., Schmidtobreick, & Sterzik, M. The formation of a massive protostar through the disk accretion of gas. *Nature* **429**, 155-157 (2004).

6. Sako, S. et al. No high-mass protostars in the silhouette young stellar object M17-SO1. *Nature* **434**, 995-998 (2004).

7. Zhang, Q., Hunter T. R. & Sridharan, T. K. A Rotating Disk around a High- Mass Young Star. *Astrophys. J.* **505**, L151-L154 (1998).

8. Shepherd, D., Claussen, M. J. & Kurtz, S. E. Evidence for a Solar System- Size Accretion Disk Around the Massive Protostar G192.16-3.82. *Science* **292**, 1513-1518 (2001).

9. Cesaroni, R., Felli, M., Jenness, T., Neri, R., Olmi, L., Robberto, M., Testi, L. & Walmsley, C.M. Unveiling the disk-jet system in the massive (proto)star IRAS 20126+4104. *Astron. Astrophys.* **345**, 949-964 (1999).

10. Sargent, A. I. Molecular clouds and star formation. I - Observations of the Cepheus OB3 molecular cloud. *Astrophys. J.* **218**, 736-748 (1977).

11. Blitz, L. & Lada, C. J. H2O masers near OB associations. *Astrophys. J.* **227**, 152-158 (1979).

12. Evans, N. J., et al. Far-infrared observations of the Cepheus OB3 molecular cloud. *Astrophys. J.* **244**, 115-123 (1981).

13. Hughes, V. A., & Wouterloot, J. G. A. The star-forming region in Cepheus A. *Astrophys. J.* **276**, 204-210 (1984)

14. Rodríguez, L. F., Garay, G., Curiel, S., Ramirez, S., Torrelles, J. M., Gomez, Y. & Velazquez, A. Cepheus A HW2: A powerful thermal radio jet. *Astrophys. J.* **430**, L65-L68 (1994).

15. Hughes, V, Cohen, R. & Garrington, S. High-resolution observations of Cepheus A. *Mon. Not. R. Astron. Soc.* **272**, 469-480 (1995).

16. Torrelles, J. M., Gómez, J. F., Rodríguez, L. F., Curiel, S., Ho, P. T. P., Garay, G. The thermal radio jet of Cepheus A HW2 and the water maser distribution at 0.08″ scale (60 AU). *Astrophys. J.* **457**, L107-L111 (1996).

17. Gómez, J. F., Sargent, A., Torrelles, J. M., Ho, P.T.P., Rodriguez, L.F., Canto, J. & Garay, G. Disk and Outflow in Cepheus A-HW2: Interferometric SiO and $HCO^+$ Observations. *Astrophys. J.* **514**, 287-295 (1999).

18. Rodríguez, L. F., Ho P. T. P., & Moran, J. Anisotropic mass outflow in Cepheus A. *Astrophys. J.* **240**, L149-L152 (1980).

19. Curiel S. et al. Large proper motions in the jet of the high-mass YSO Cepheus A HW2. *Astrophys. J.* submitted (2005).

20. Rodríguez, L.F., Torrelles, J. M., Anglada, G., Marti, J. VLA Observations of Brightness Enhancements moving along the Axis of the Cep A HW2 Thermal Jet. *Revista Mexicana de Astronomia y Astrofisica* **37**, 95-99 (2001).

21. Torrelles, J. M., Gómez, J. F., Garay, G., Rodríguez, L. F., Curiel, S., Cohen, R. J. & Ho, P. T. P. Systems with $H_2O$ maser and 1.3 centimeter continuum emission in Cepheus A. Astrophys. J. **509**, 262-269 (1998).

22. Furuya, R. S., Kitamura, Y., Wootten, A., Claussen, M. J. & Kawabe, R. Water maser survey toward low-mass young stellar objects in the northern sky with the Nobeyama 45 meter telescope and the very large array. *Astrophys. J. Supp.* **144**, 71-134 (2003).

23. Ho. P. T. P., Moran, J. M. & Lo, K. Y. The Submillimeter Array. *Astrophys. J.* **616**, L1-L6 (2004).

24. Loren, R. B. & Mundy, L. G. The methyl cyanide hot and warm cores in Orion - Statistical equilibrium excitation models of a symmetric-top molecule. *Astrophys. J.* **286**, 232-251 (1984).

25. Pankonin, V., Churchwell, E., Watson, C. & Bieging, J.H. A methyl cyanide search for the earliest stages of massive protostars. *Astrophys. J.* **558**, 194-203 (2001).

26. Shu F., Najita, J., Ostriker, E. & Shang, H. Magnetocentrifugally Driven Flows from Young Stars and Disks. V. Asymptotic Collimation into Jets. *Astrophys. J.* **455**, L155-L158 (1996).

27. Hildebrand, R., The determination of cloud masses and dust characteristics from submillimetre thermal emission. *Quarterly Journal of the Royal Astronomical Society* **24**, 267-282 (1983).

28. Williams, S. J., Fuller, G.A. & Sridharan, T.K. The circumstellar environments of high-mass protostellar objects. I. Submillimetre continuum emission. *Astron. Astrophys.* **417**, 115-133 (2004).

29. Hunter, T., Churchwell, E., Watson, C., Cox, P., Benford, D. & Roelfsema, P. 350 Micron Images of Massive Star Formation Regions. *Astron. J.* **119**, 2711-2727 (2000).

30. De Buizer, J., Osorio, M. & Calvet, N. Observations and Modeling of the 2-25 $\mu$m emission from high mass protostellar object candidates. *Astrophys. J.*, in press (2005).

**Correspondence** should be addressed to N. A. P. (npatel@cfa.harvard.edu)

**Acknowledgement:** SC acknowledges support from DEGAPA/UNAM, CONACyT grants 43120−E and from the Submillimeter Array project. G.A., J.F.G. and J.M.T. are supported by AYA2002-00376 grant (including FEDER funds). G.A. acknowledges support from Junta de Andalucía. 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. We are grateful to the people of Hawai'ian ancestry on whose sacred mountain we are privileged to be guests.

Fig. 1.—

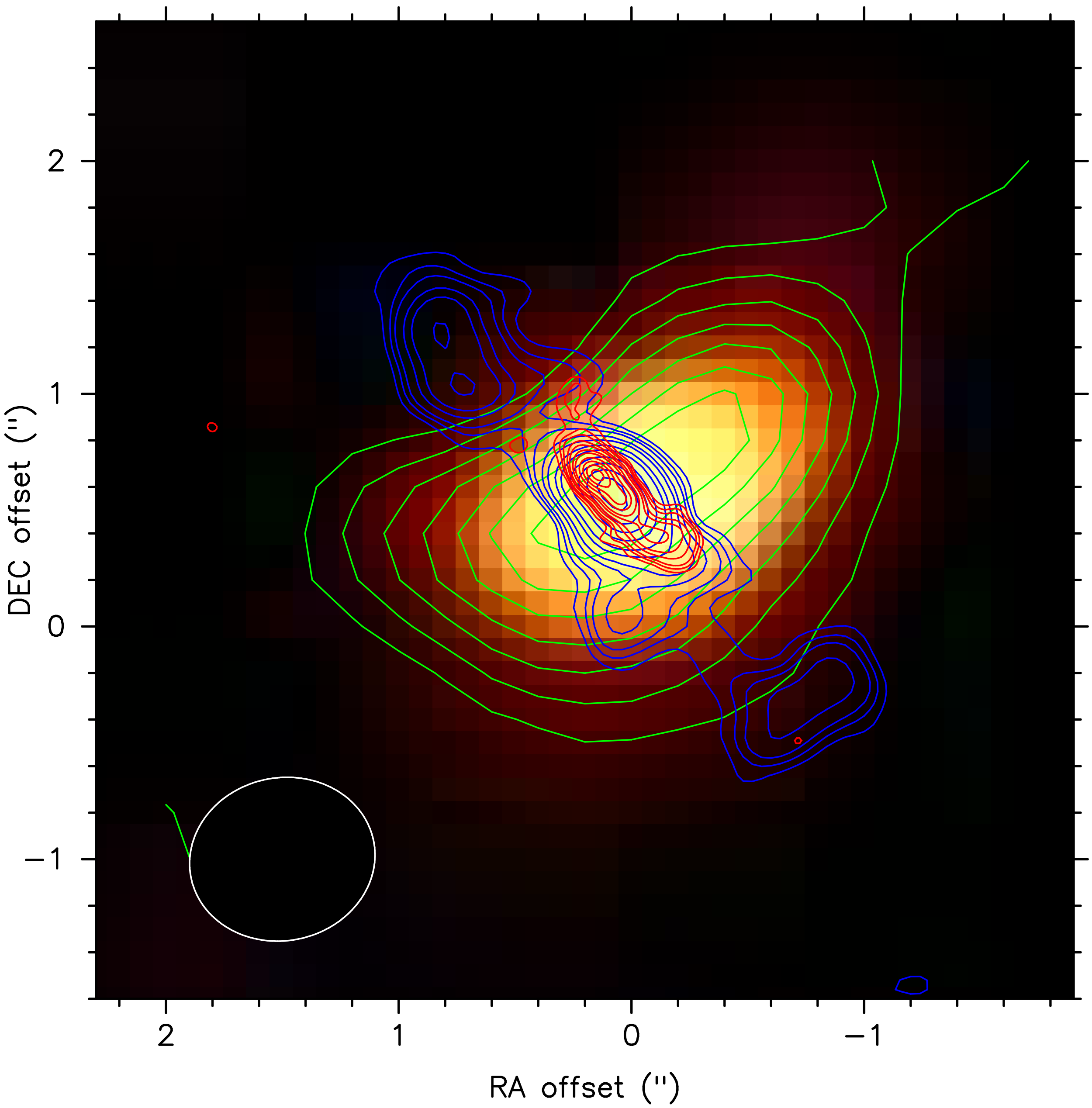

**Fig. 1:** Dust continuum emission of the Cepheus A HW2 protostar at 327 GHz (halftone image ranging linearly from 0 to 1.5 Jy beam$^{-1}$) and integrated intensity in the $CH_3CN$ J=18-17 (K=0,1,2,3) line emission from -35 to 30 km s$^{-1}$ line-of-sight velocity range (contour levels from 5 to 40 Jy beam$^{-1}$ km s$^{-1}$ in steps of 5 Jy beam$^{-1}$ km s$^{-1}$). $CH_3CN$ has been shown to trace high density ($10^6$ cm$^{-3}$) gas in massive star-forming regions[24,25]. The SMA beam size was $0.''8 \times 0.''7$ with a PA of $-78.^o6$ (left lower corner). This angular resolution is by far the highest reached at submillimeter wavelength observations (e.g., compared to single-dish observations, we have more than an order of magnitude greater angular resolution). Blue contours show the 3.6 cm wavelength continuum emission from a well collimated jet, while red contours show the 1.3 cm wavelength continuum emission from the inner part of the jet[16,20]. The protostar is believed to be located at the origin of this elongated jet. The absolute astrometric error in the alignment of the VLA and SMA observations is $\simeq 0.''2$. The elongation in both dust and $CH_3CN$ emission is nearly perpendicular to the circumstellar thermal jet, strongly supporting the disk interpretation. The deconvolved disk radius is $\simeq$330 AU. The submillimeter observations were carried out using 7 of the 8 available antennas of the SMA in the extended array configuration with a maximum baseline of 226 meters. The observations were carried out on 30 August 2004 and the receivers tuned to 321 GHz. With this tuning, we had the methyl cyanide ($CH_3CN$) J=18-17, K=0,1,2,3...9 lines in the upper sideband and the $10_{29}$ - $9_{36}$ water maser transition in the lower sideband. Submillimeter water masers were found to be associated with the HW2 and HW3c sources (Patel et al. in preparation).

Fig. 2.—

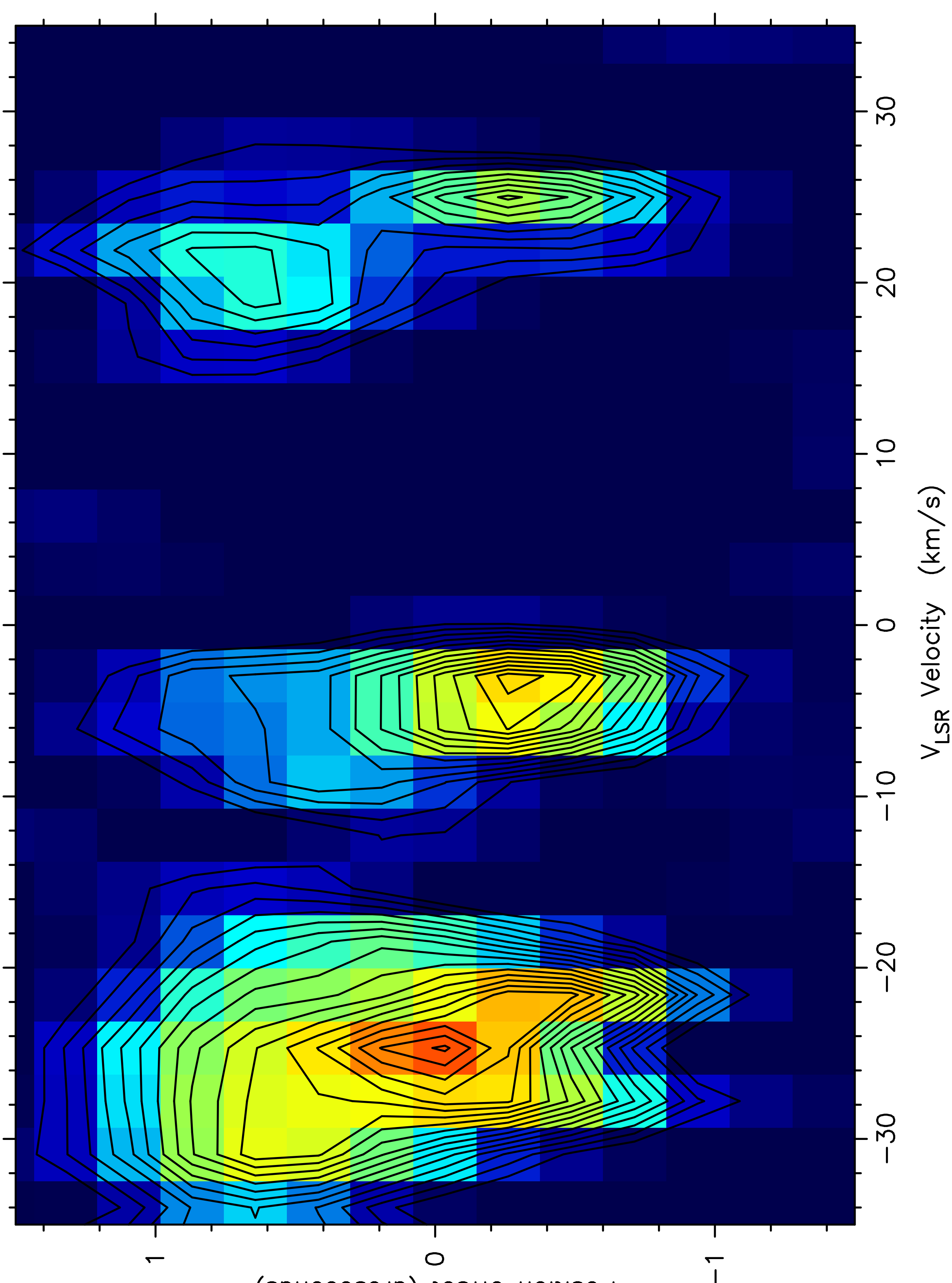

**Fig. 2:** Position-velocity map of $CH_3CN$ emission along the major axis of the elongated structure shown in figure 1 with position angle –$53^o$ (with respect to North, with East as positive). The contour levels are from 0.3 to 1.5 Jy beam$^{-1}$ every 0.1 Jy beam$^{-1}$. The position offset is measured along the major axis, with positive offset corresponding to the southeast part and negative offset towards the northwest part of the disk. The $0''$ position offset corresponds to the peak of the integrated intensity. The K = 0 and 1 components are blended. K=4 and higher lines were not detected. The reference frequency was chosen to be at the J=18-17, K=2 line of $CH_3CN$. We interpret the velocity shift of ∼6 km s$^{-1}$ over $0\overset{''}{.}5$ seen in the K=2 and K=3 emission to be due to rotational motion and estimate a binding mass of 19±5 $M_\odot$.