MOLECULAR EMISSION FROM CIRCUMSTELLAR DISKS

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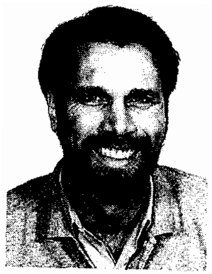

Abstract

The interpretation of millimeter-wave molecular line emission from circumstellar disks has been complicated by the high opacity of the lines, emission from the parent molecular clouds, and emission from molecular outflows. Observations of the disk around GM Auriga overcome the latter two of these problems and show that GM Auriga is another good example of a circumstellar gas disk in Keplerian rotation around a pre-main sequence star.

I. Introduction

Circumstellar disks begin as flattened clouds of hydrogen gas with miniscule amounts of the heavier elements that might later collect into planets and other large bodies. The gas can as yet only be observed in millimeter-wave emission lines from trace constituents such as CO. These long wavelengths require aperture synthesis arrays for adequate resolution of the disks, and the best resolution provided by existing arrays is still more than 100 AU at the distances to the nearest young stars, several times the size of the present Solar System. Fortunately, several objects have disks that appear to extend over several thousand AU making it possible to study the gas directly. The interpretation of these observations is controversial, however, largely because the emission is not easily distinguishable against that from the surrounding molecular cloud (*e.g.*, Beckwith and Sargent 1993a, and references therein).

The molecular line observations provide two important tools for the study of these disks: the direct images show the size and inclination angle, and they have sufficient velocity resolution to determine if the gas is, in fact, orbitting the stars. Furthermore, a direct image is persuasive support for the disk interpretation of infrared continuum observations (Adams, Lada, and Shu 1988, hereafter ALS; Strom *et al.* 1989; Beckwith *et al.* 1990, hereafter BSCG) that otherwise relies on indirect arguments to infer the distribution of the circumstellar material. (Although we note that in no case known to us does the emission imply a unique geometry which must be a disk.)

Between 100 and several thousand AU beyond the star, there should be some memory of cloud collapse, but there is as yet no reliable theoretical framework to guide our observational expectations for the cloud-disk boundary. The disks could be sharply bounded, or they might blend smoothly into the cloud as the Keplerian velocities decrease to the same levels as the cloud turbulence. Temperatures in this region are low; emission from very cold particles and molecular lines will be at far-infrared and millimeter wavelengths.

The first system detected in molecular lines was around the pre-main sequence star HL Tauri (Beckwith *et al.* 1986; Sargent and Beckwith, 1987, 1991). HL Tau is a classical T Tauri star with a strong bipolar jet. It is the brightest T Tauri star in millimeter-wave continuum emission in the Taurus cloud implying one of the most massive disks. Maps of the ^{13}CO line emission show an elongated, apparently flattened pancake, suggesting an almost edge-on disk.

Observations of the gas along the disk plane demonstrate that the highest velocities are close to the star ($\lesssim$200AU) with the red- and blue-shifted components on opposite sides; lower velocities are spread out to over several thousand AU. The "rotation" curve has the general appearance of Keplarian orbital motion and was thus interpreted by Sargent and Beckwith (1987). This interpretation is not unique, and it becomes more complicated at higher angular resolution (Sargent and Beckwith 1991; Guilloteau 1993). In particular, the low velocity gas no longer exhibits a regular pattern; there is substantial contamination by ambient cloud emission and by emission from a molecular outflow emerging perpendicular to the disk in maps at the lower relative velocities.

The few other observed systems have their own ambiguities. T Tauri is almost face-on making the rotation curve signature difficult to distinguish; the data are, nevertheless, consistent with Keplerian orbits (Weintraub, Masson, and Zuckerman 1989). DG Tauri shows considerable interference from its cloud and outflow (Sargent and Beckwith 1993). IRAS 16293–24 (Mundy *et al.* 1990) is a young, embedded binary in which disk structure has not clearly been resolved. Similarly, the structure around the obscured star L1551 IRS 5 is very difficult to interpret as disk-like (Sargent *et al.* 1988; Padin *et al.* 1989); there is much material from the surrounding cloud and molecular jet which adds to the molecular emission.

The molecular lines used for these observations probably have high optical depths in the disks ($\gtrsim$100) and appreciable opacity in the surrounding material, as well. Although interferometer measurements discriminate against relatively smooth, large-scale emission, it is difficult to distinguish the disk emission from clumpy cloud emission at scales of a few thousand AU, where the velocities are low (Sargent and Beckwith 1993). At the distance of the Taurus cloud, the best angular resolution to date, $1''.5$, is still inadequate to resolve the material at radii less than 100AU which produces the observed far infrared spectral energy distributions of the disks.

As part of a longer term programme to study the outer parts of these disks, we have carried out two new studies. The first is to calculate molecular line emission expected from disks, using as input parameters the best available interpretations to the spectral energy distributions (Beckwith and Sargent 1993b). The second is to search for disks in which some combination of fortuitous circumstances favors direct study of the disk itself without contamination by the background cloud (Koerner, Sargent, and Beckwith 1993).

II. Opacity of Disk Emission Lines

The appearance of a disk at specific velocities (*channel maps*) depends on the inclination to the line of sight, its size or outer radius, and the line emissivity within it. Here, we consider only disks with inclinations of order 45° and assume they are sharply bounded. The velocity profiles of emission lines integrated over the spatial extent of the disk will be characteristically double-peaked with maxima occurring at the orbital velocities at the edges (Horne and Marsh 1986). In each channel map, the emission traces out those portions of the disk whose velocity projected onto the line of sight matches the observing velocity. In general, maps of the disks at different velocities will show a series of arcs, such as those shown in Figure 1. The arcs are small and closed at high velocities and large and open at the low velocities. Arcs at velocities on opposite sides of the systemic velocity are mirror images of each other.

Disks viewed exactly edge on will also have this pattern of arcs, but they are not observed as such because of projection. Nearly face on disks should exhibit little discernible structure.

The optical depths at line center for the $J = 1 - 0$ line of ^{13}CO, are several hundred or more for disks such as that around HL Tau. Even for disks which are rather large ($R_d \gtrsim 1000$AU), the optical depths remain much greater than unity, the lower average surface density being compensated by lower temperatures which preferably increase the number of molecules in the low rotational states.

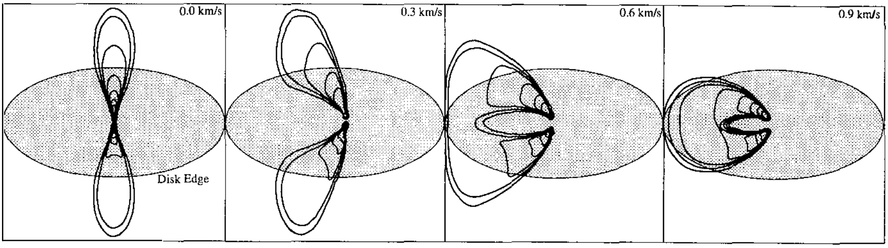

Figure 1: The appearance of a Keplerian disk at inclination 45° to the line of sight in four channel maps near a star of $1M_\odot$ in the $J = 1 - 0$ line of ^{13}CO from Beckwith and Sargent (1993b). Only the redshifted emission is shown making only one half of the disk visible. The outline of the disk is the dashed line; the contours are brightness temperature in increments of 2 K starting at 2 K. The disk has a radial temperature gradient $T(r) \sim r^{-1/2}$. A slight flaring of the disk introduces the asymmetry in the vertical lobes.

Thus, although ^{13}CO maps can indicate the general morphology of T Tauri disks, the lower rotational transitions are probably too opaque to serve as useful probes of the physical conditions.

The disk emission in the outer parts of the arcs always dominates the total emission if the temperatures decrease more slowly than inversely with the radius, the usual case for T Tauri star disks (BSCG). Therefore, those arcs which have the largest apparent area on the sky are responsible for the most emission. This dominance of the outer parts of the disk in the line strengths means that the integrated line intensity is quite sensitive to the temperatures in the outer parts of the disk. Line strengths for the stars which have been mapped in ^{13}CO indicate that the outer disks are indeed quite warm (Sargent and Beckwith 1993), warmer, in fact than they would be if heated only passively by the stars or through the normal release of accretion energy (ALS; BSCG). In fact, the line strengths support the evidence from the far-infrared spectral energy distributions that the temperature in the disks decreases only as $T(r) \sim r^{-1/2}$.

III. GM Auriga

GM Auriga is an older T Tauri star, approximately 2×10^6yr, with a relatively low luminosity, $0.7L_\odot$. The far infrared spectral energy distribution indicates an extensive disk with a relatively flat spectrum ($T(r) \sim r^{-0.55}$), while the relative paucity of near infrared radiation suggests clearing of the central regions (Strom, Edwards, and Skrutskie 1993; BSCG). Although it is a classical T Tauri star with Hα emission, there is little evidence of a wind from this star (Cabrit *et al.* 1993). The combination of no wind and a hole in the inner part suggests that the star is not actively accreting. GM Aur should, therefore, be relatively free from the confusing effects of outflow unlike the case of HL Tau as noted by Guilloteau (1993). It has had a longer time to establish orbital motion in the outer parts of disk. It is an ideal candidate to test against the calculations described in the previous section.

The left hand side of figure 2 is a series of maps of GM Aur in the $J = 2 - 1$ line of ^{13}CO at 1.3mm made with the Owens Valley millimeter-wave array (Koerner, Sargent, and Beckwith 1993). The resolution is $3''.5 \times 5''.8$ (525×870AU). There is a large-scale velocity gradient across the face of what we will interpret to be a disk. On the north-east side, the relative velocities are all positive (red shifts); on the south-west, they are negative (blue shifts). We interpret the emission to come from a disk whose axis has a position angle of about 50° on the sky and an inclination angle of 30° along the line of sight.

The right hand side of figure 2 is a series of synthesized maps for an inclined disk in Keplerian rotation. We assumed the emissivity falls with radius as a sum of two different exponential functions: a core which has a half width of 150AU and an extended part which has a radius of about 1000AU. The model calculations reproduce the gross features seen in the maps and several of the details, as well. The central velocity channels have distinct arc-shapes, the arcs exhibiting mirror symmetry about an axis at a position angle of 140°, perpendicular to the major axis of the disk ellipse. The model not only matches the overall shape of the emission but also the relative intensities. It is striking that in the central two channels around 14 km s^{-1} both observed and synthetic emission is weaker. This weakness is the result of relatively small areas in the disk for which the central velocities are in resonance, the decrease in area resulting in decreasing overall emission. The agreement between the models and the observations is not perfect – note for example the confusing blobs that are seen in the highest velocity maps. Again, these demonstrate the sensitivity of the interferometer to clumping in the ambient medium; they presumably have little or nothing to do with the disk. Nevertheless, the overall agreement between the calculations and the observations is quite good.

GM Aur is another example in which both the morphology and the dynamics of the molecular emission suggest a molecular disk around the star. The disk extends over many hundreds of astronomical units. The line intensities require the outer parts of the disk to be warmer than they would be under heating by accretion or direct illumination by the central star. This result is consistent with the strength of the 1.3mm continuum flux, 180mJy, and the relatively flat spectral energy distribution.

A stronger test of the disk model requires better spatial resolution and, perhaps, observation of molecules less abundant than ^{13}CO. Already, it seems likely that HCO^+ may be a good tracer of the dense parts of disks (Blake, van Dishoeck, and van Langevelde 1993). Although technically difficult, higher resolution (sub-second of arc) observations would match the observed scales with those responsible for the spectral energy distributions. There are rather strong expectations of disk structure based on the observations of the spectral energy distributions in the far infrared at scales of a few tens of AU. It is at that point that our observations will really begin to test current disk theory.

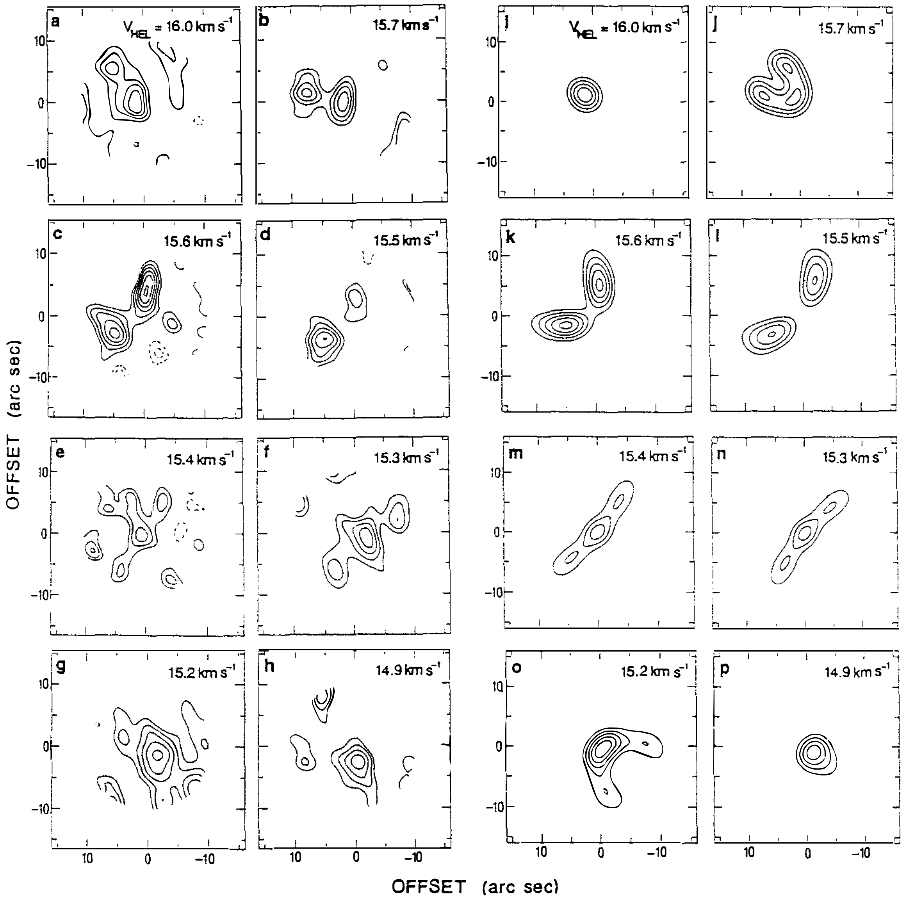

Figure 2: The two columns on the left show a series of channel maps of GM Auriga; the right hand columns are artificial maps calculated from a model of an inclined disk with the major axis at 140° (Koerner, Sargent, and Beckwith 1993).

REFERENCES

Adams, F. C., Lada, C. J., and Shu, F. H. 1988, *Ap. J.*, **326**, 865 (ALS).

Beckwith, S. V. W. and Sargent, A. I. 1993a, in *Protostars and Planets III*, ed. E. H. Levy and J. I. Lunine (Tucson:U. Arizona Press), p. 521.

Beckwith, S. V. W. and Sargent, A. I. 1993b, *Ap. J.*, **402**, 280.

Beckwith, S., Sargent, A. I., Scoville, N. Z., Masson, C. R., Zuckerman, B., and Phillips, T. G. 1986, *Ap. J.*, **309**, 755.

Beckwith, S. V. W., Sargent, A. I., Chini, R., and Güsten, R. 1990, *Astron. J.*, **99**, 924 (BSCG).

Blake, van Dishoeck, and van Langevelde 1993

Guilloteau, S. 1993, in *The Cold Universe*, ed. T. Montemerle, in press.

Horne, K. and Marsh, T. R. 1986, *MNRAS*, **218**, 761.

Koerner, D. W., Sargent, A. I., and Beckwith, S. V. W. 1993, *Icarus*, submitted.

Mundy, L. G., Wooten, H. A., and Wilking, B. A. 1990, *Ap. J.*, **352**, 159.

Padin, S., Sargent, A. I., Mundy, L. G., Scoville, N. Z., Woody, D. P., Leighton, R. B., Scott, S. L., Seling, T. V., Stapelfeldt, K. R., and Terebey, S. 1989, *Ap. J. Let.*, **337**, L45.

Sargent, A. I. and Beckwith, S. V. W. 1987, *Ap. J*, **323**, 294.

Sargent, A. I., Beckwith, S., Keene, J., and Masson, C. R. 1988, *Ap. J.*, **333**, 936.

Sargent, A. I. and Beckwith, S. V. W. 1991, *Ap. J. Lett.*, **382**, L31.

Sargent, A. I. and Beckwith, S. V. W. 1993, in *URSI/IAU Symposium 140: Interferometry with Millimeter and Submillimeter Arrays*, ed. M. Ishiguro and R. Kawabe (ASP conference Series, San Francisco: Bookcrafters), in press.

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., and Skrutskie, M. F. 1989, *Astron. J.*, **97**, 1451.

Strom, S. E., Edwards, S., and Skrutskie, M. F. 1993, in *Protostars and Planets III*, ed. E. Levy and J. Lunine (U. Arizona Press: Tucson).

Weintraub, D. A., Masson, C. R., and Zuckerman, B. 1989, *Ap. J.*, **344**, 915.