OBSERVED CHARACTERISTICS OF PROTOSTELLAR DISKS

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ABSTRACT. Detailed structures in the central parts of several star forming regions have been observed with the Nobeyama 45-m telescope. The disk and flow systems observed in L1551, R Mon, GL490 and S106 regions show the following common characteristics: (1) Double-peaked appearance with a thin central part around the IR source, (2) Cavities exist on both polar sides of the disk, and the low velocity molecular flow fits the shape of the cavity wall and the pattern of the reflection nebula. (3) The flow seems to be accelerated gradually along the wall of the cavity. An empirical model based on these results is discussed.

1. MOLECULAR LINE OBSERVATIONS OF PROTOSTELLAR DISKS

Compact molecular disks surrounding the IR protostars and/or PMS stars have been observed by various authors with NH_3, CS and CO molecular lines (e.g. Rodriguez in these proceedings). Such disks are particularly interesting to investigate in much more detail because (1) the disk is a key-link in the star formation process which is not understood yet, it is a direct product of the contraction of the molecular gas and also a direct source of material for the star formed in it, (2) the disk may play an essential role in producing an energetic flow from the central protostar, and (3) the disk may form a planetary system in its central part if the central star is not too massive to blow the disk away by its powerful wind and radiation.

For the understanding of such problems we need a very high resolution both in space and in frequency. 1-2 arcsec resolution with enough S/N ratio will reveal essential characteristics of the central part of the disk such as the density distribution, the temperature distribution, the velocity curve, etc. The 10-20 arcsec resolution can scarcely distinguish such fine structures; with this resolution, however, we can obtain the general characteristics of the disk such as the shape, the correlation with the molecular flow and other related phenomena, the general velocity field structure, etc.

M. Peimbert and J. Jugaku (eds.), Star Forming Regions, 275–285.

We have observed some selected star-forming regions in various molecular lines using the Nobeyama 45-m Telescope. Here we report recent results of CO observations of L1551 and R Mon as well as CO, HCN, HCO^+ observations of GL490 and S106 which show characteristics common to protostellar disks, especially in relation to molecular flows and to optical features.

2. L1551 (1): DISK AND CAVITY

The rotating disk around L1551 IRS-5 observed with the CS 1-0 line (Kaifu et al. 1984) shows a double-peaked structure centered at the position of IRS-5 and elongated perpendicularly to the flow axis. This shape may be an indication of "nozzle" structure which collimates the molecular flow, or the central part of the disk may be geometrically thin due to its formation mechanism. The latter case could correspond from a theoretical point of view to the self-gravitational contraction of a non-spherical cloud (Hayashi et al. 1982).

Figure 1 shows some of the results from our high resolution CO observations of the central part of L1551 bipolar flow. The detailed results will be published elsewhere. The inner edges of the red- and blue-shifted flow components with relatively low flow velocities (ΔV_r = 2-3 km s^{-1}) show smooth and round shapes which fit very well the outer edges of both sides of the CS disk.

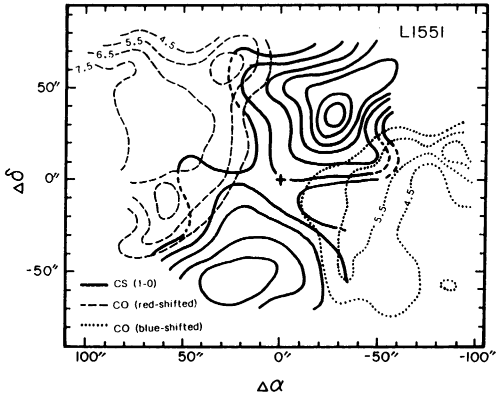

Figure 1.
The shapes of the inner regions of the red-shifted (ΔV_r=+2.3±1 km s^{-1}) and blue-shifted (ΔV_r=-2.7±1 km s^{-1}) flows observed with the CO 1-0 line are compared with the rotating disk around IRS-5 (shown as a cross at the center) observed with the CS 1-0 line by Kaifu et al.(1984). Contours are $T_a^* \cdot V_r$ in K km s^{-1}.

The blue-shifted flow has a clear shell-like structure. We could not find a sharp "nozzle" like feature nor compact high velocity component near the IRS-5 which are expected for the stellar-wind acceleration mechanism of the flow. Instead, the flow velocity becomes lower when we observe the position closer to the disk as we will describe in the following section.

An extended faint optical nebulosity is seen in the SW side of

IRS-5. Mundt and Fried (1983) reported the existence of a compact ionized jet which seems to be ejected directly from IRS-5. The root of the blue-shifted flow, which has a velocity very close to that of the disk (ΔV_r = -1.7 to -2.7 km s^{-1}) coincides almost exactly to the optical nebulosity as can be seen in Figure 2. This observational fact shows that the molecular flow coexists with the reflection nebula produced by dust in the wall of the cavity scattering the light from central star.

Combining this with the shell-like appearance mentioned above, we can conclude that the molecular flow, at least in its inner regions, actually flows in the shell along the walls of the cavity in the polar sides of the disk. The disk is probably supplying the molecular gas and dust to form the bipolar flow, because we observe the lowest velocity flows in the interface region between the disk and the flow. Such a picture will be discussed again for R Mon in section 4.

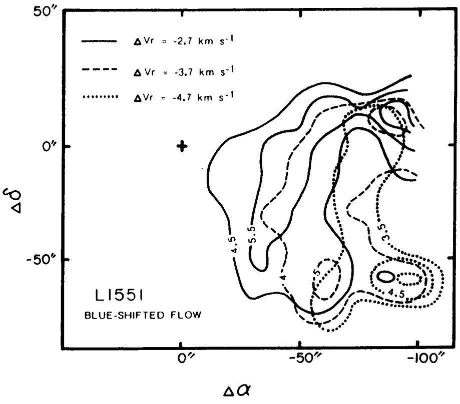

Figure 2.
The blue-shifted flow with a very low flow velocity (ΔV_r = -2.2±0.5 km s^{-1}) is overlayed on an optical photograph of the L1551 region showing the optical jet and faint nebulosity taken by Mundt et al.(1983).
The IRS-5 is at the (0",0") position.

3. L1551 (2): ACCELERATION OF THE FLOW

A higher velocity CO flow of L1551 is in general observed at a larger distance from the central protostar IRS-5. This can be seen very clearly especially in the blue-shifted component. Figure 3 shows the distribution of the low-velocity part of the blue-shifted flow in the vicinity of the disk. The shell-like feature shifts outward when the radial velocity relative to the central velocity (i.e.the disk velocity) increases. Such tendency can be seen in Figure 4 which displays a larger area (about 14' x 14'). Both red and blue flows shift to distant positions for high flow velocities. The ratio of velocity shift to the projected distance d can be roughly estimated from the postion-velocity diagram along the flow axis (Uchida et al. 1987) to be

$$\frac{\Delta V_r}{d} = \frac{4-6}{0.1} \left(\frac{\mathrm{km\ s^{-1}}}{\mathrm{pc}} \right)$$

within the range of $d \lesssim 0.2$ pc. The expanding shell model may be able to explain such a shift of shell feature, but the required velocity field would not be simple. Another difficulty of the expanding shell model is that the shell should be observed as two velocity components clearly separated. A model assuming the higher velocity flow inside the shell (one example of such a model is described by Lada 1985) also results in a velocity dependence of the shell structure as described above. But this model is also improbable because it predicts that the lower-velocity flow could be observable towards the inner side of the shell, contrary to our observational results which show a very thin shell structure with an internal hollow at lower velocities (see Figure 4).

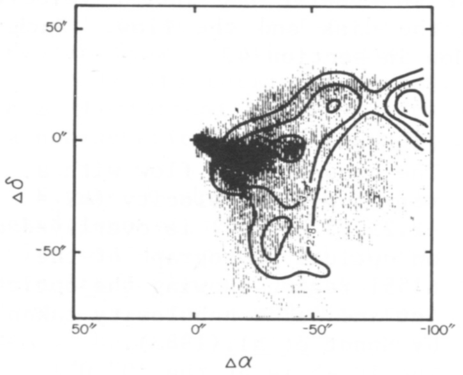

Figure 3.
The L1551 blue-shifted flow shows an apparent acceleration. The contours show the flow components integrated for 2 km s^{-1} intervals centered at V_r which is shown in the figure.

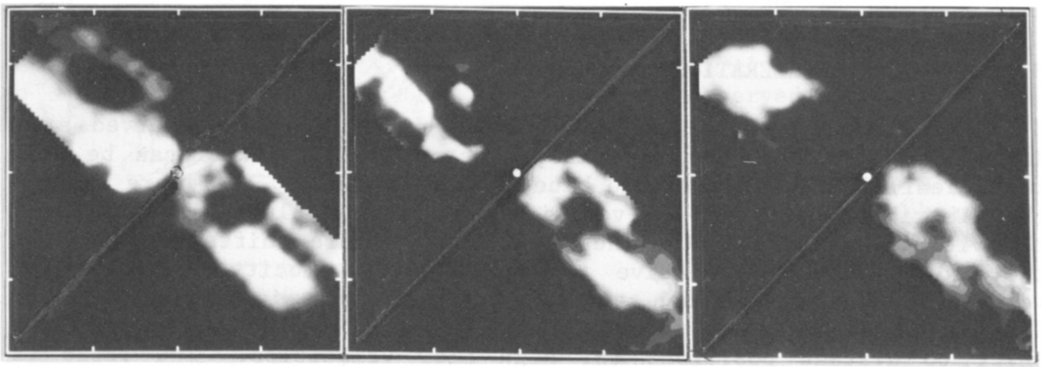

Figure 4. The CO bipolar flow structure of L1551 at various flow velocities. The relative V_r's with respect to the assumed central velocity are: ΔV_r=+1.8 ± 0.5 and -2.2 ± 0.5 km s^{-1} (left), ΔV_r=+5.3 ± 0.5 and -4.2 ± 0.5 km s^{-1} (middle), ΔV_r=+10.8 ± 2.5 and -8.2 ± 2.5 km s^{-1} (right). Flows are more distant from IRS-5 (shown as a white dot) at higher flow velocities. The area shown above is about 14x14 arc min.

An alternative explanation is that the flow is confined in the paraboloid-shaped cavity walls and is accelerated along the walls. As illustrated in Figure 5, such a flow, tilted slightly from the plane perpendicular to the line of sight, will result in the parabolic-shaped shell feature shifting farther away with higher radial velocity. In the area near the central star, the two velocity components of the flow are predicted by this model too, but the flow is expected to be observed mainly from one side of the shell and the other side tends to be buried in the strong emission from the ambient gas or disk component due to the geometrical effect which makes the wall of this side of the cavity nearly perpendicular to the line of sight. However, the slightly red-shifted component is expected to appear in the very inner region of the blue-shifted flow and vice versa, depending on the geometry and the velocity field of the flow. The flow around R Mon, which we will describe below, might be an example of such an effect.

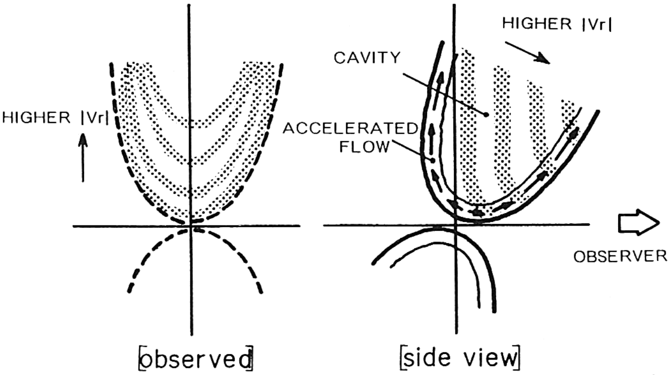

Figure 5.
A schematic explanation of observed spatial and velocity structure of the L1551 bipolar flow. We assume a tilted parabolic shell and a flow being accelerated along the walls of the shell. The hatched area shows the equi-V_r contours which is expected to be observed as the apparent "moving away shell" structure.

4. CO DISK AND FLOW AROUND R MON

R Mon is a protostar candidate which sits at the vertex of the core of the famous reflection nebula NGC 2261. Canto <u>et al.</u>(1981) observed this region in the CO 1-0 transition and found a disk-like cloud with a size of 4' x 2' elongated in the E-W direction, and bipolar-type velocity components in the north and south of R Mon. This area seems to be more or less isolated without heavy background or ambient emission and is a good source to investigate the nature of the disk. Brugel <u>et al.</u> (1984) found high velocity [SII] line emission which indicates that the ionized bipolar flows in the N-S direction extend about 10 arcsec from R Mon. HH-39 is located about 7' north on the direction of the ionized flow and Walsh and Malin (1985) reported the exsistence of a faint filament which connects HH-39 with NGC 2261.

We have observed the 160 x 140 arcsec area around R Mon with the 15 arcsec beam of the CO 1-0 line. A clear bipolar flow and a disk feature with cavities in its polar sides were found. The geometrical characteristics of the disk surrounding R Mon seem to be similar to those of the L1551 disk.

Figure 6 shows the structure of the blue-shifted flow and the disk. The blue-shifted flow fits surprisingly well NGC 2261 as shown in the top left. On the other hand, the disk component has double peaks in the east and west side of R Mon and shows a remarkable deep bay in the central north. The blue-shifted flow fits in this deep bay like a zig-saw puzzle. Thus the flow and the reflection nebula should sit in the deep cavity of the disk. A shallow cavity also exists in the southern side of R Mon and the red-shifted flow fills it. The R Mon disk should therefore be geometrically thin at its center. The slightly blue-shifted component shown in the middle of of Figure 6 is the most remarkable feature which indicates that the lowest velocity flow is acturlly an interface between the disk and the molecular flow along the walls of the cavity.

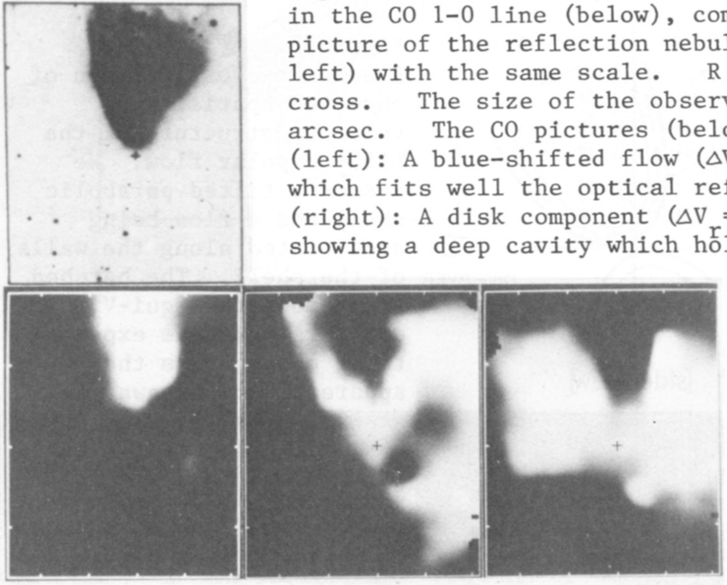

Figure 6. Three diferent features of R Mon observed in the CO 1-0 line (below), compared with an optical picture of the reflection nebula NGC 2261 (upper left) with the same scale. R Mon is shown by a cross. The size of the observed area is 160 x 140 arcsec. The CO pictures (below) show: (left): A blue-shifted flow (ΔV_r=+8.0±0.25 km s^{-1}) which fits well the optical reflectin nebula. (right): A disk component (ΔV_r=+9.75±0.25 km s^{-1}) showing a deep cavity which holds the blue-shifted molecular flow and NGC 2261 in it. (middle): very low velocity component of the blue-shifted flow (V_r=-0.75±0.25 km s^{-1}); a clear shell structure between the flow and the disk is seen.

The structure of the higher-velocity flow of R Mon is compact and we could not resolve it with our 15 arcsec beam and with the 15 arcsec grid. Also the flow velocities (ΔV_r) are quite low compared with other bipolar flow sources. Figure 7 is a position-velocity map along the N-S direction which is almost parallel to the flow axis. An apparent acceleration similar to that of L1551 is seen, though it is much smaller ($\Delta V/d$ = 1/0.1 km s^{-1} / pc). It may partly be due to the geometrical effect caused by the smaller inclination of the R Mon disk flow from the plane of the sky, but probably the main reason is that the flow acceleration itself is weaker than that in L1551, as the observed flow is relatively compact and also the line width is smaller than 3 km s^{-1} Both in L1551 and in R Mon the molecular flow near the central IR sources seem to have double-velocity-component structure which is expected in the accelerated shell model described in the former section

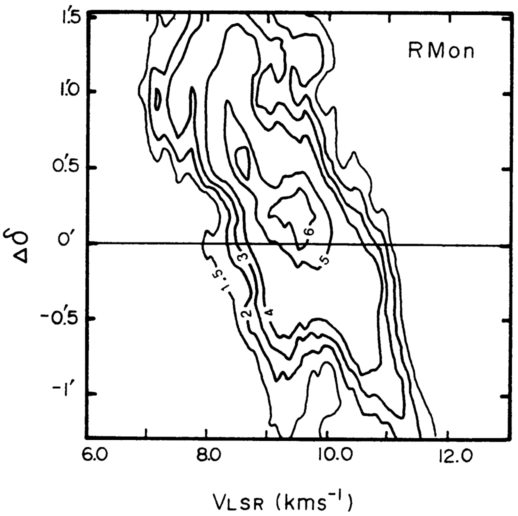

Figure 7.
A δ-V_r diagram along the central axis of the CO flow of R Mon (N-S direction), showing an acceleration of the flow. The contour is in T_a^* (K).

as seen in Figure 7, although it is diffecult to distinguish the secondary velocity component from the disk component.

5. GL490 AND S106

We have observed R Mon in the CS 1-0, CS 2-1 and HCN lines. It was found that these lines are very weak even in their disk component. This fact suggests that the gas density in the R Mon disk is relatively low ($n_{H2} \lesssim 10^4$ cm^{-3}) and can hardly excite these transitions. On the other hand, some molecular flow objects are known to emit HCN, HCO$^+$ and CS lines. Such sources are generally embedded in dense molecular clouds and are accompanied by massive disks or cores. Thus the density of the disk seems to vary considerably from source to source.

The star forming regions in dense molecular cores GL490 and S106 have been observed at Nobeyama in the CO, HCN, and HCO$^+$ molecular lines. Figure 8 shows the distributions of the CO flow and the HCO$^+$ disk component (Snell _et al._ 1984, and Kawabe _et al._ 1987). The resolution is not high enough to resolve the structure of the CO flow, but the disk component has double-peaked structure with a thin central part again. The remarkable feature in this map is the shell-like structure in the disk elongated along both edges of the red-shifted and blue-shifted flows. These features compose the cavities in both polar sides of the disk holding the CO outflows in them, similarly to L1551 and R Mon. The same features can be seen in the HCN distribution, though they are relatively weaker compared with the central condensation. These shell-like patterns observed in GL490 in HCO$^+$ and HCN are probably due to dense molecular gas of the disk accelerated from the surface of the cavity walls into the flow. As GL490 is a relatively luminous IR source (L_{IR} = 1400 $L_\odot$), its flow may be powerful enough to push the massive gas out to form such large cavities.

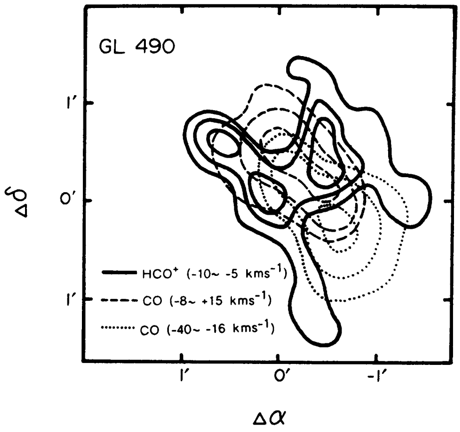

Figure 8.
Disk and flow components of GL490 observed in HCO^+ (Kawabe et al. 1986) and CO (Snell et al. 1984).

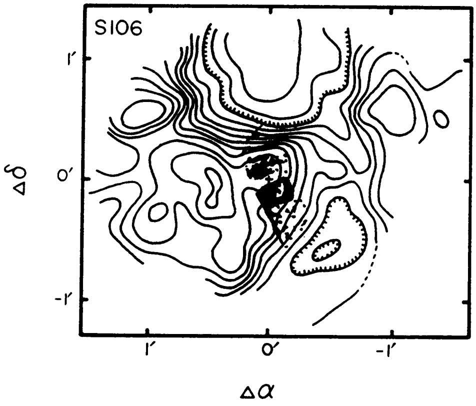

Figure 9.
Central part of the CO disk component of S106 (Kaifu and Hayashi 1987). The integrated V_r range is -1.5 to -2.3 km s^{-1}. The compact bipolar H II region observed by Bally et al. (1983) is also shown as a filled area.

A CO map showing the disk component of S106 is presented in Figure 9 (Kaifu and Hayashi 1986). The S106 disk observed by Bally and Scoville (1982) is huge, with a size of 0.9 pc x 0.4 pc and with a very compact bipolar H II region sitting at the center (Bally et al. 1983). We could not find a clear molecular flow but the CO, HCN and HCO^+ distributions around the central velocity show similar disk-like features again with: a thin central part, strong emissions in the east and in the west of the IRS, and large cavities in the polar sides. The direction of the elongation of the central part of the disk is parallel to that of the dust layer observed by Bally et al.(1983). S106 is in the final stage of the formation of a massive star and the disk seems in the process of being disrupted. Even at this stage we can see the structure common to that observed in the sources at earlier stages of star formation.

6. A PICTURE OF THE PROTOSTELLAR DISK AND THE FLOW SYSTEM

We summarize the characteristics of the disks around protostellar sources obtained from our observations as follows.

1. The observed disks commonly show double-peaked structure with a thin central part, suggesting the existence of cavities in the polar sides of the disk.
2. The inner region of the molecular flows with low flow velocities ($\Delta V_r = 1$-2 km s^{-1}) fit very well the edges of the disks. In the case of L1551 they show very smooth shapes instead of the nozzle-like feature which is expected for the stellar-wind hypothesis.

3. The inner region of blue-shifted flows also fit well the optical reflection nebulae. Thus the reflection nebulae, such as NGC 2261, are actually due to scattered light from the cavity walls corresponding to the inner regions of the molecular flows, and can be seen through the cavities.
4. The molecular flows are likely to be accelerated along the walls of the cavities, at least in the vicinity of the disks.

A schematic model obtained by combining the elements summarized above is shown in Figure 10. The disk is expected to show well-defined structure and characteristics in its central part, while the diffuse outer part of the disk might be difficult to be distinguished from ambient clouds. Therefore the inner part of the disk and the inner regions of the molecular flow should be observed with higher resolution and with higher sensitivities in order to investigate detailed physical processes governing star formation and the activities associated to it.

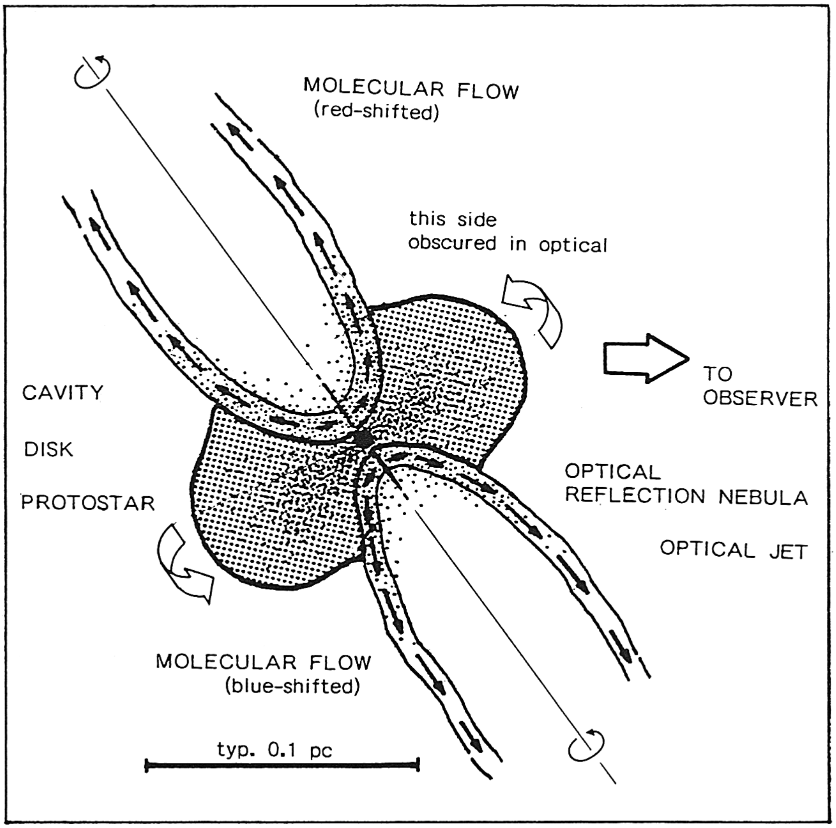

Figure 10. A schematic model of the disk and flow system around a protostar.

One of the important characteristics of the disks is rotation. So far rotating disks have been repored for several sources (e.g., Kaifu et al. 1984, Hasegawa et al. 1984, Vogel et al. 1985, Little et al.1985), although the rotation is not clear in some other disk features. The very attracting idea that the L1551 molecular flow may be rotating (Uchida et al.1986) might become a key to solve the acceleration mechanism, because it suggests an existence of a rotating magnetic disk which pushes up the accreting gas along the walls of the shell toward the polar directions (Uchida and Shibata 1985). The rotation of the inner part of the disk as well as the possible rotation of the root of the flow should be examined carefully for various sources.

The optical (ionized) jets are illustrated in the central part of the flow in Figure 10. The acceleration mechanism of the ionized jet is also suggested to be magnetic origin by Uchida and Shibata (1984), but so far no clear evidence was found whether the ionized jet has an acceleration mechanism different from or common to that of the molecular flow.

This work is part of a collaborative project in the Nobeyama Radio Observatory. The main collaborators are: T. Hasegawa, S.S. Hayashi, Y.Uchida, K. Shibata, M. Ohishi, and R. Kawabe.

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THOMPSON: Most of the objects at the centers of molecular outflows have high velocity (100-300 km/s) ionized winds. These are within IAU of the central objects. It would be interesting to hear comments on the relationship between these winds and the molecular outflows.

EVANS: Russ Lavreault, Steve Beckwith, and I have been observing Bγ and Bα in T Tauri stars with CO outflows. If we use the stellar wind models of Simon *et al.* to derive mass loss rates from the infrared lines, we find poor agreement with the mass loss rates derived from the CO. Consequently, a better theoretical understanding of the infrared line formation is required before we can tie together the CO and infrared observations.

HARVEY: It is possible that your HCN map of S106 is consistent with Bieging's map, considering the different angular resolutions and sensitivities?

KAIFU: Our beam is 14" to 18" for CO, HCN, HCO^+ and CS 2-1. All these molecular line observations gave pretty similar maps, without an indication of a compact central disk with a large velocity gradient as that obtained by Bieging with a 16" beam.

BALLY: Ron Snell and I have some unpublished H_2CO 6-cm absorption maps obtained at the VLA showing that the deepest absorption occurs toward the compact radio continuum source located at the center of S106. This indicates the presence of very dense gas in the direction of the supposed disk.

SHU: There was a reference in Luis Rodríguez's talk that perhaps the CS disk in L1551 was not rotating after all. Could you please comment on this?

KAIFU: Batrla (1985) claims that he could not find any rotation from CS 1-0 observations obtained with the 100-m MPIFR telescope. Our result (Kaifu *et al.* 1984) was obtained from a two-dimensional map while his result was obtained from only one (N-S) strip. We plan more extensive observations of this object.

COHEN: Are you sure about the geometry of the cavities? Axon and Taylor have suggested that in Orion a high-velocity wind blows a biconical cavity with rather straight sides. Low-velocity outflow along the walls of the cavity would then have surfaces of constant radial velocity which appear curved, like hyperbolic sections. Do you think such a model would fit your observations, for example in L1551?

KAIFU: At least from our observational data, the shapes of the roots of both the red and blue shifted flows of L1551 and that of the redshifted flow are very shallow and round. I feel that it is difficult to explain such shapes by a biconical shaped cavity with a narrow open angle.