BIPOLAR OUTFLOWS AND STELLAR JETS

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ABSTRACT. A wealth of data is now available on the energetic mass outflows that are associated with young stellar objects. This phenomenon is thought to occur at a very early stage in the evolution of stars of almost all masses. The discovery of this energetic event was first made through observations of the rapidly expanding molecular gas that surrounds many of these young stellar objects. A review of the physical properties, including the energetics and morphology, of the expanding molecular gas is presented in this paper. In addition, the role these energetic winds play in affecting the dynamics of the parental molecular clouds is also discussed. Finally, the results of detailed studies of the structure and kinematics of the high velocity molecular gas are reviewed and the evidence for existance of wind-swept cavities and molecular shells within the clouds are presented.

1. INTRODUCTION

It has been known for a number of years that stars experience mild episodes of mass loss during their evolution to the main-sequence. However, recent observations have revealed that many of these young stars also undergo a shorter but much more energetic phase of mass outflow. It is this brief but energetic phase of activity that will be the focus of this review. It is thought that this activity occurs within the first 10^5 years of a star's lifetime when the star is deeply embedded in its parental molecular cloud. It is for this reason that this remarkable phase of stellar evolution was first revealed by observations of emission from highly disturbed molecular gas at millimeter wavelengths. Recently, there has been a wealth of data obtained at radio, optical, and infrared wavelengths that bear on the nature of this brief evolutionary phase of stars. Since it is impossible to cover all aspects of the current study of outflows, I will restrict this review to the observations of the high velocity molecular gas. Such a focus seems appropriate, since it is primarily

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by observations of the high velocity molecular gas that the magnitude and widespread occurance of this activity were first revealed. Other aspects of the study of outflows are presented in accompanying articles in this volume.

The most ubiquitous tracer of the molecular gas component in the galaxy is the millimeter wavelength emission of CO. It is in the emission of the J=1→0 transition of CO that only 10 years ago the high velocity molecular gas motions were first detected by Zuckerman, Kuiper, and Rodriguez-Kuiper (1976) and Kwan and Scoville (1976) towards the core of the Orion Molecular Cloud. Figure 1 shows a spectrum of the J=2→1 transition of CO in this region. This spectrum shows emission extending over a total velocity extent of nearly 180 km s^{-1}, substantially greater than the 5 km s^{-1} that is more commonly seen in this molecular cloud. Although, the line widths of CO throughout the molecular cloud indicate motions is excess of the sound speed, the enormous velocities seen in the core of Orion must arise from a distinctly different origin. The extremely high velocity emission in Orion is also very localized to a region with an angular extent of only 40 arcsec or a linear extent of 0.09 pc (Solomon, Huguenin, and Scoville 1981; Knapp et al. 1981). Since the discovery of the high velocity emission in Orion, many other star formation sites have been shown to have a similar phenomena occurring within them. The velocity extent of these other star formation regions is typically much smaller than that of the Orion region, but the velocities are still substantially greater than the average linewidths seen throughout these clouds.

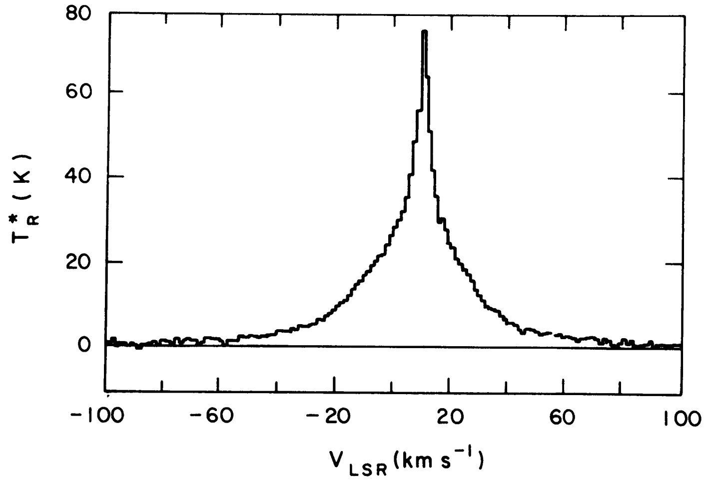

Figure 1. Spectrum of the J=2→1 transition of ^{12}CO towards the outflow in the Orion molecular cloud obtained with the Five College Radio Astronomy Observatory 14 m telescope.

Estimates of the mass in regions of high velocity emission rule out the possibility that the gas motions seen are due to the gravitational infall of material or the rapid rotation of part of the cloud. This high velocity motions must be due to expansion of the molecular gas in these star forming regions. Such expansion may be driven by either some impulsive event, as was suggested by Kwan and Scoville (1976) for the Orion region, or by a steady wind blowing from the newly formed stars that are deeply buried within the cloud. Confirmation that the high velocities observed in CO are truely due to the outflow of material was provided by the measurements of the proper motions of the H_2O masers in the Orion region (Genzel et al. 1981). Observations of both the H_2O masers and high velocity SiO emission (Wright et al. 1983) suggest that the outflow in Orion originates from the infrared source IRc2. Presumably, the high velocity gas seen toward other star formation regions must also arise from expansion of material away from one of the newly formed stars. In a few cases measurements of the proper motions of Herbig-Haro objects (Cudworth and Herbig 1979; Herbig and Jones 1981; 1983) have confirmed that the high velocities are indeed due to the outflow of material from other young stellar objects.

Often times the outflowing molecular gas is found not to be symmetrically expanding away from the young star, but instead appears to have a bipolar configuration as was first noted in the L1551 outflow (Snell, Loren and Plambeck 1980). Such a bipolar nature of outflows can be detected by the asymmetrical distribution of the emission in the line wings; Figure 2 shows CO spectra taken in three directions toward the bipolar outflow in GL490 that illustrate the striking asymmetry in the shape of the line wings. The high velocity molecular gas in these regions has probably been accelerated by a collimated, energetic stellar wind. In some cases the presence of such a collimated stellar wind can be directly inferred by the detection of optical or radio jet-like emission (Mundt and Fried 1983; Mundt, Stocke, and Stockman 1983; Strom, Strom, and Stocke 1983; Cohen, Bieging, and Schwartz 1982).

In general, regions of energetic mass outflow are identified by broad CO emission lines with total velocity extents of 10 to 180 km s^{-1} that are restricted to very small areas of the molecular clouds, usually surrounding an embedded young stellar object. In some cases the bipolar nature of these outflows can be used to distinguish the outflows from other motions within the cloud. Though these outflows are primarily discovered and studied by their millimeter wavelength emission of CO, the submillimeter and far-infrared transitions of CO (Storey et al. 1981; Goldsmith et al. 1981) as well as emission from SO (Plambeck et al. 1982), SiO (Wright et al 1983), HCO^+ (Vogel et al. 1984; Loren et al. 1984; Wootten et al. 1984), H_2CO (Wootten, Loren, and Bally 1984), CS (Kawabe et al. 1984; Takano 1985), NH_3 (Takano et al. 1985), and OH (Mirabel et al. 1985) can provide valuable information on the structure, density, and chemistry of the hypersonic molecular gas. For brevity, this review will be restricted to primarily a discussion of the emission from the low lying rotational states of CO.

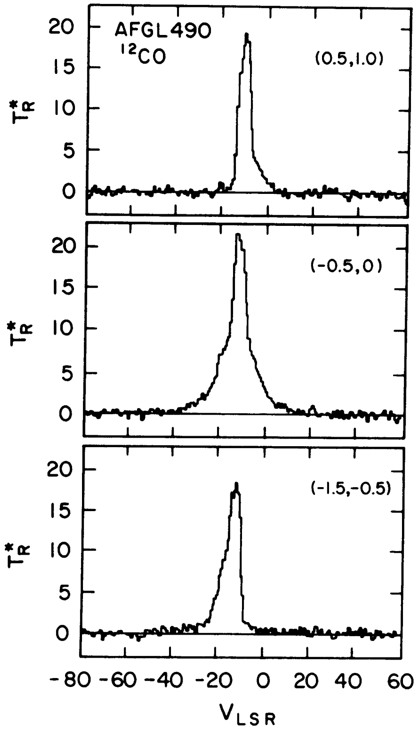

Figure 2. ^{12}CO spectra obtained in three directions towards the bipolar outflow in AFGL490. The position of each spectrum is indicated by its offset in arcmin relative to the infrared source.

To date more than 67 molecular outflows have been detected (Lada 1985), these outflows have been found to be associated with stellar objects with bolometric luminosities of 1 to 10^5 solar luminosities. The high velocity CO emission in many of these regions has been known to exist for many years, but was incorrectly interpreted as due to collapse or rotation of the cloud. Such confusion is not surprising since outflow regions like Mon R2 (Bally, Lada, and Wolf 1986) have the bulk of their ^{12}CO emission arising from the outflowing gas and not the ambient cloud material. For isolated clouds, it is very likely that when the CO line widths exceed 10 km s^{-1} that such motions are due to the presence of expanding molecular gas driven by winds from a young stellar object.

2. PHYSICAL PROPERTIES AND ENERGETICS

The observations of the high velocity molecular emission are an excellent means of deriving the energetics of these mass outflows, since the energy and momentum in the molecular gas have been accumulated over the lifetime of the outflow. Estimates based on observations of CO have indicated that the mass of high velocity molecular gas is very large and thus requires the presence of powerful stellar winds. Because of the importance of determining the energetics of these outflows, it is useful to review the techniques used to derive the mass and ultimately the momentum and energy of the outflowing molecular gas.

2.1. Mass

The mass of high velocity molecular gas is usually estimated from observations of the CO emission. The determination of the mass requires, not only measurements of the integrated CO emission, but also measurements of the optical depth, excitation temperature, and the abundance of CO. In many studies the mass and consequently the energy and momentum of the molecular outflow is based on assuming that the lines are optically thin and that the excitation temperature and abundance of CO are the same as the ambient gas. As we will see, the energetics of these outflows can be underestimated if care is not taken in properly deriving the mass of the expanding molecular gas.

2.1.1. Optical Depth. The determination of the optical depth of the CO lines is important to accurately estimate the column density of molecular gas. A number of investigators has shown that the high velocity ^{12}CO emission is optically thick even though the CO emission is very weak (Plambeck, Snell, and Loren 1983; Bally 1982; Lada and Harvey 1981). The most straightforward technique to measure the optical depth of the hypersonic gas is by observing various isotopic lines of CO, particularly ^{13}CO. Several studies have examined the optical depth issue in detail (Snell et al. 1984; Margulis and Lada 1985) and they show that the observed ^{12}CO/^{13}CO ratio in the hypersonic gas is substantially less than the expected isotopic ratio of 65 to 90. Spectra of the J=1→0 and J=2→1 transitions of ^{12}CO and ^{13}CO toward the Orion molecular outflow are shown in Figure 3 (from Snell et al 1984) and illustrate the strength of the ^{13}CO emission in the high velocity gas. The observed ^{12}CO/^{13}CO ratios for these two transitions in Orion are shown in Figure 4 as a function of velocity. In the several sources that have been studied, the optical depth of the high velocity J=1→0 emission of ^{12}CO is between 1 and 5. Therefore, corrections for the optical depth are essential for accurate estimates of the mass.

In addition, the optical depth can be strongly dependent on the radial velocity of the high velocity emission. The data shown in Figure 4 indicate that the optical depth decreases for gas at higher and higher radial velocity. The high optical depth in the lower velocity hypersonic gas suggests that the bulk of the mass of the outflowing gas has a relatively low outflow velocity. In the highest velocity gas seen in Orion, the observed $^{12}CO/^{13}CO$ ratio in the J=1→0 transition is roughly 90 (see Figure 4), suggesting that the emission may be optically thin and that the true isotopic ratio is terrestial.

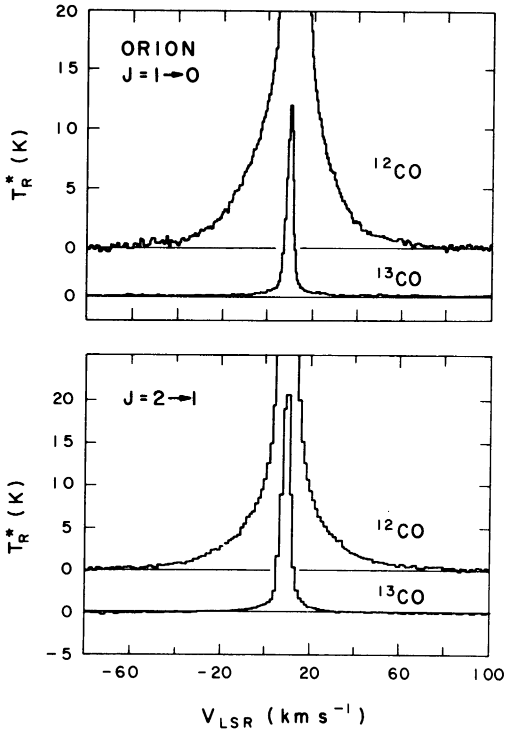

Figure 3. Spectra of the J=1→0 and J=2→1 transitions of ^{12}CO and ^{13}CO towards the Orion molecular outflow (from Snell et al. 1984).

2.1.2. Excitation Temperature. Since it is neither practical nor possible to observe all of the rotational transitions of CO, it is necessary to estimate the populations of the unobserved levels to determine the total CO column density. The excitation temperature can be derived from observations of two or more transitions of CO. Observations of the J=1→0 and J=2→1 transitions of CO have been made by Snell et al. (1984), Levreault (1985), and Margulis and Lada (1985) in a number of outflows and the CO J=3→2 transition have been made by Phillips et al. (1982) in L1551. The most accurate technique for deriving the excitation temperature uses the ratio of optical depths

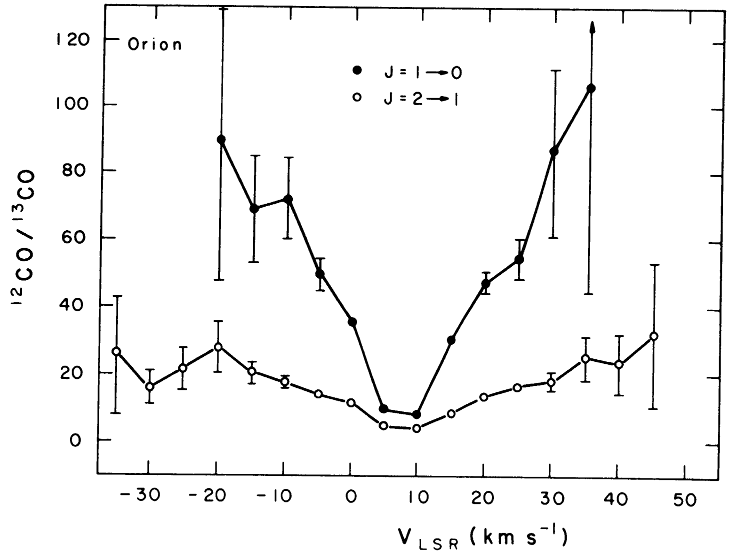

Figure 4. The observed $^{12}CO/^{13}CO$ ratio in the J=1→0 and J=2→1 transitions for the Orion molecular outflow (from Snell et al. 1984).

and not the ratio of intensities of the different CO transitions. The few multi-transition studies that have been completed suggest that the excitation temperature (and presumably the kinetic temperature) of the high velocity gas is comparable to that of the surrounding ambient gas, independent of velocity. The accelerated molecular gas is thus very cold, suggesting that the CO emission arises from cool, postshock gas, unlike the H_2 emission that must arise in much hotter gas closer to the shock front. Therefore, the assumption that the excitation temperature is similar to the ambient gas may be a good approximation for many high velocity outflows.

2.1.3. Abundance of CO. Finally, the determination of the total gas column density of high velocity gas requires a knowledge of the CO abundance. Unfortunately, the abundance of CO has not been derived in any high velocity source and, in fact, is known relatively poorly even for the ambient cloud material. Changes in the CO abundance that may occur are due to the high temperature chemistry possible as the ambient gas passes through the stellar wind shock. Until better data is available, it will be necessary to assume that the abundance of CO in the high velocity gas is the same as that for the ambient gas.

2.1.4. Distribution of Masses. The mass of high velocity molecular gas has been determined for a number of outflows and is found to vary from 0.01 to 100 solar masses. A histogram of the mass of high velocity gas for 46 outflows is shown in Figure 5 based on the data from Lada (1985), Edwards and Snell (1984), Snell *et al.* (1984), Fischer *et al.* (1985) Levreault (1985), and Myers *et al.* (1986). The references cited above are also the source of data for the statistics on other outflow properties discussed later. The statistics represented in the histogram in Figure 5 are not by any means complete or unbiased, but instead reflect the properties of the small sample of outflows that have been studied in detail. The median mass of the outflows is 3 solar masses, but in many cases the masses are lower limits since optical depth corrections have not been made. The large mass of high velocity gas suggests that the bulk of the material is swept-up ambient cloud material and not material from the stellar wind itself.

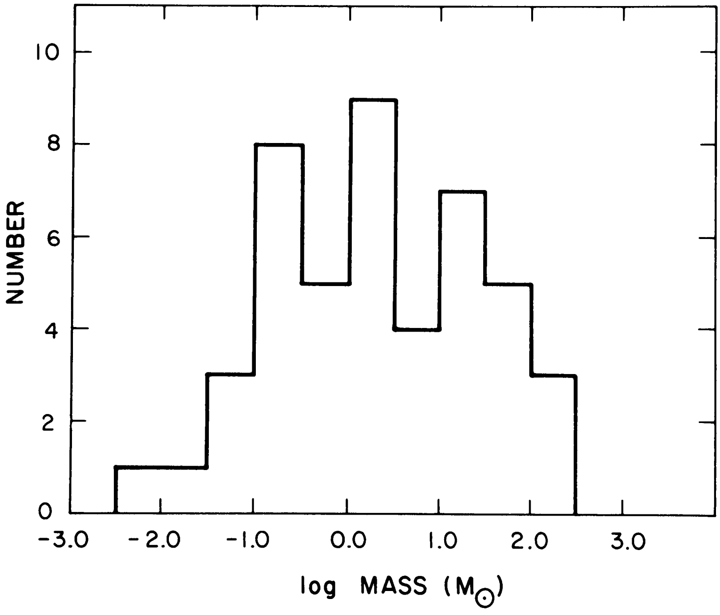

Figure 5. A histogram of the mass of expanding molecular gas in 46 outflow regions, from the references cited in the text.

2.2. Filling Factor

The large optical depths found for the high velocity ^{12}CO emission are actually very surprising since the high velocity emission, in general, is extremely weak. This situation is possible only if a very small fraction of the telescope beam is filled with high velocity CO emission. From the observations of the strength of the CO emission (T_R) and the derived values of the excitation temperature (T_{ex}) and optical depth (τ), the filling factor (ff) of high velocity gas within the telescope beam can be estimated using the following expression:

$$ff = T_R \,/\, [T_{ex}\,(1-e^{-\tau})].$$

Values of ff in the high velocity gas have been found to vary from 0.1 to 1 (Plambeck, Snell, and Loren 1983; Phillips et al. 1982; Snell et al. 1984; Margulis and Lada 1985). In the outflows in Orion, NGC2071, and S140 the filling factor is a strong function of radial velocity; the highest velocity gas in these outflows has a filling factor of 0.1, while the lower velocity gas has a filling factor that approaches unity. Since these outflows are well resolved by the current observations, the small filling factor in the highest velocity gas suggests that the expanding molecular gas must be clumped on size scales smaller than the resolution of the telescope. In addition, the smooth line profiles that are seen require that there be numerous, small clumps within the telescope beam. If this clumpy model is correct, then the number of clumps must decrease with increasing outflow velocity and these clumps must fill only a small fraction of the surface of the outflow and probably a much smaller volume.

2.3. Velocities

The velocity extent of the CO emission found in a number of outflows suggest that the expansion velocity varies from 5 to 100 km s^{-1}. The maximum velocity extent observed is dependent on the signal to noise of the observations; in examples shown in Bally and Lada (1983) the full velocity extent is greatly increased when better signal to noise is available. Unfortunately, only the radial component of the motion is actually measured and, since these outflows are in many cases collimated, projection effects can cause one to vastly underestimate the true outflow velocity. A histogram of the full velocity extent observed in 48 outflows is presented in Figure 6. The median value is 25 km s^{-1}.

Although these velocites are large when compared to the bulk of the molecular emission in clouds, they are much smaller than the line widths of the Brα and Brγ hydrogen recombination lines of 100 to 300 km s^{-1} (Persson et al. 1984, Simon et al. 1981; Black and Willner 1984) seen toward the embedded stellar sources. Presumably, the recombination lines arise in the partially ionized stellar wind located near the young stellar objects. The low velocities observed for the molecular outflow are consistent with a model in which the bulk of the high velocity molecular gas is accelerated ambient gas. If momentum is conserved, one would expect the molecular velocities to be much smaller than the wind velocities, since the mass of the swept-up gas is much larger than that in the stellar wind.

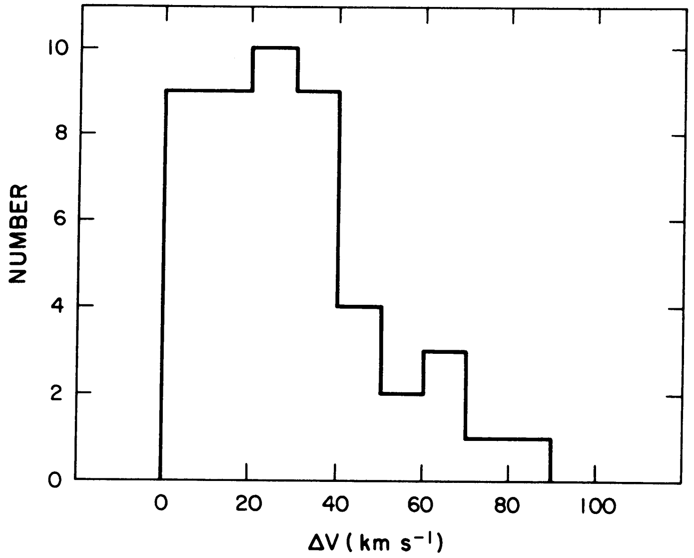

Figure 6. A histogram of the full velocity extents observed in the ^{12}CO J=1→0 emission for 48 molecular outflows.

2.4. Momentum and Energy

The momentum and energy can be determined based on the observed velocities and the computed masses. Both of these quantities are generally lower limits since the optical depth corrections are not usually made and the geometry of the outflows are poorly known. Nevertheless, the momenta (10^{-1} to 10^{2} $M_{\odot}$ km s^{-1}) and energy (10^{43} to 10^{48} ergs) found for the outflows are enormous.

The rate of deposition of momentum and energy into the molecular gas by the stellar wind can be determined if the dynamical timescale of the outflow is known. A crude estimate of this timescale can be made based solely on the observed transverse size of the outflow and radial velocity. The dynamical timescale determined in this fashion is highly dependent on the assumed geometry and orientation of the outflow and is probably the dominant source of uncertainty in determining the outflow energetics. Dynamical timescales found by this method range from 10^{3} to 10^{5} years with the vast majority having values near 10^{4} years. Based on the measured dynamical timescale, momentum, and energy, the mechanical luminosity and momentum flux in the outflow can be estimated. It is generally assumed that these outflows are in a phase in which the motion of the expanding molecular gas is governed by the conservation of momentum between the stellar wind and the swept-up molecular gas. Adopting this assumption permits the mass flux in the stellar wind to be estimated. For a stellar wind velocity of 200 km s^{-1}, the mass flux for different outflows is found to vary from 10^{-7} to 10^{-3} solar masses yr^{-1}. In addition, the mechanical luminosity in the expanding molecular gas can be estimated and is found to vary from 10^{-5} to 10^{3} solar luminosities. Typically the luminosity of the stellar wind is much larger than that of the expanding molecular gas. Thus, only a small fraction of the wind energy is transferred to the expanding molecular gas. The bulk of the wind energy must be radiated away by the post-shock gas. Evidence for substantial luminosity from the shocked gas has been found by Edwards _et al_. (1986) using the coadded IRAS data for the L1551 outflow.

A histogram of the mechanical luminosity in the expanding molecular gas in 48 outflows is shown in Figure 7. The median luminosity for this sample is 0.1 solar luminosities. We can compare the mechanical luminosity in the outflowing molecular gas to the bolometric luminosity of the stellar source presumed responsible for the outflow. A plot of the stellar luminosity versus the mechanical

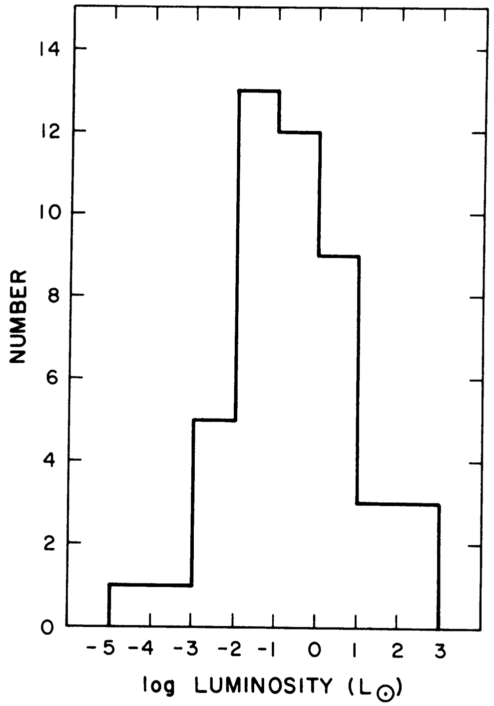

Figure 7. A histogram of the log of the mechanical luminosity in the expanding molecular gas for 48 molecular outflows.

luminosity is shown in Figure 8; it is clear from this plot that a good correlation exists between these two quantities - a fact first noted by Bally and Lada (1983). On average the mechanical luminosity in the molecular gas is only 0.1% of the bolometric luminosity of the stellar source, but the mechanical luminosity in the stellar wind can be as large as a few percent of the bolometric luminosity. Nevertheless, sufficient energy in the stellar photons is present to provide the energy of the expanding molecular gas, even if much of the energy is radiated away at the shock front. Alternatively, if a comparison is made between the photon momentum flux and the momentum flux in the expanding molecular gas, the photon momentum flux is two orders of magnitude too small. Therefore, it is unlikely that the radiation pressure can drive a stellar wind necessary to explain the observations of the expanding molecular gas.

If the radiation pressure is not responsible for driving the outflow, then it is somewhat surprising that such a good correlation between the photon luminosity and the mechanical luminosity in the molecular gas exists. This correlation implies that the same energy

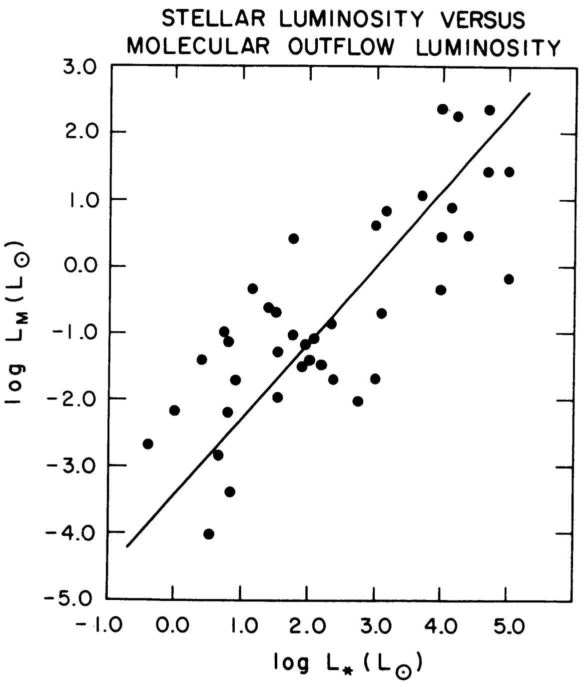

Figure 8. A plot showing the correlation between the mechanical luminosity in the expanding molecular gas and the bolometric luminosity of the driving stellar source.

source that provides the stellar luminosity is also responsible for powering the stellar winds. Such an energy source might be the accretion of material onto these young stellar objects which may provide the photon luminosity of the embedded stellar sources (Adams and Shu 1986) and also power the outflows (Torbett 1985; Pudritz 1985; Uchida and Shibata 1985).

2.5. Summary of Outflow Properties

The observations suggest that the hypersonic molecular gas is likely accelerated ambient cloud gas and not gas from the stellar wind itself. Since the expanding molecular gas is thought to be driven by collimated winds from these young stellar objects, observations of the hypersonic molecular gas can provide valuable information on the energetics of the stellar winds integrated over time. A summary of the median properties of the molecular outflows and that inferred for the stellar winds based on the data cited earlier is presented in Table 1.

TABLE 1

Average Molecular Outflow and Stellar Wind Properties

Mass	$3\ M_\odot$
Kinetic Temperature	$20\ K$
Full Velocity Extent	$25\ km\ s^{-1}$
Energy	10^{45} ergs
Dynamical Timescale	$2x10^{4}$ years
Luminosity	$0.1\ L_\odot$
Mass Loss Rate in Stellar Wind	$10^{-6}\ M_\odot\ yr^{-1}$
Luminosity of Stellar Wind	$10\ L_\odot$

3. OUTFLOW MORPHOLOGY

One of the most surprising discoveries connected with the study of molecular outflows has been the morphology of the expanding molecular gas. The molecular gas is not expanding spherically away from the star, as one might expect, but instead is often collimated into two oppositely directed jets of gas (Snell, Loren, and Plambeck 1980). Presumably, this structure results from the stellar wind itself being initially collimated. In the case of the L1551 outflow this hypothesis is confirmed by the detection of jet-like radio continuum and optical emission originating from within 10^{14} cm of the stellar object and is aligned with the expanding molecular gas (Cohen, Bieging, and Schwartz 1982; Bieging, Cohen, and Schwartz 1984; Snell _et al._ 1985; Mundt and Fried 1983).

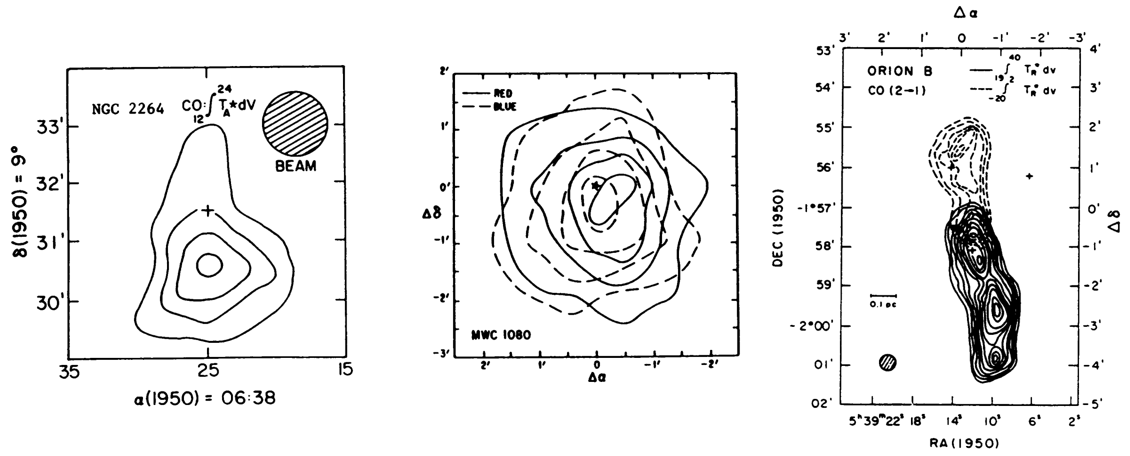

Figure 9. Examples of the three types of outflow morphlogy discussed in the text. In all three examples the solid contours delineate the integrated intensity of the redshifted CO emission and the dashed contours the blueshifted CO emission. The data are from Schwartz *et al.* (1985), Canto *et al.* (1984), and Sanders and Willner (1985).

Although many outflows appear collimated, others show quite different morphologies. Lada (1985) divided molecular outflows into three catagories based on their morphology: 1) symmetrical outflows, 2) monopolar outflows, and 3) bipolar outflows. Lada found that about 75% of molecular outflows are bipolar, 15% are monopolar, and 10% are symmetrical. Examples of each type of morphology are shown in Figure 9 from Schwartz et al (1985), Canto et al (1984), and Sanders and Willner (1985). The diverse structures that are observed might all originate from a similar phenomena and only reflect variations in the viewing angle or the surrounding cloud structure. For instance, all outflows may be produced by collimated stellar winds. The few symmetrical outflows may be just those bipolar outflows that are seen nearly end on and the few monopolar outflows may just be bipolar outflows in which the stellar source is located near the front or back face of the cloud so that one of the collimated jets has little molecular material to accelerate. Alternatively, the symmetrical outflows may really arise from spherically symmetric stellar winds and the monopolar outflows from cases in which the winds originate from only one pole.

Although the majority of molecular outflows appear bipolar, the degree of collimation is highly variable and in most cases relatively poor. Such poor collimation may be in part due to either limited angular resolution or geometrical effects. Most observations are made with poorer angular resolution than would be desired. In Figure 10 the NGC2071 outflow is shown mapped at angular resolutions of 90 arcsec (Bally 1982), 45 arcsec, and 23 arcsec (Snell et al. 1984).

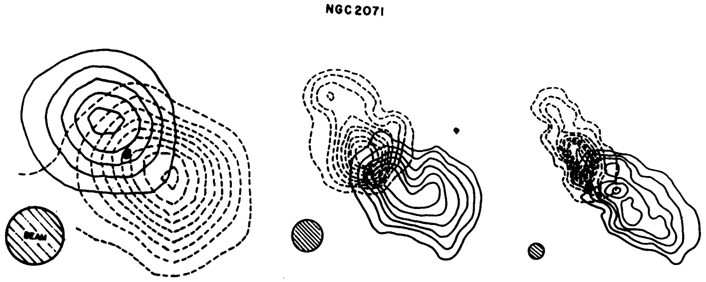

Figure 10. Contour maps of the high velocity CO emission in the NGC2071 outflow obtained at resolutions of 90, 45, and 23 arcsec (Bally 1982; Snell et al. 1984). Contours of the high velocity redshifted gas is shown by solid lines in the two maps on the right and by a dashed lines for the contour map on the left. The opposite is true for the high velocity blueshifted gas.

It is clear in this example that the apparent degree of collimation depends strongly on the angular resolution that is available.

In addition, since the outflows are presumably oriented randomly in space, intrinsically well collimated outflows may appear poorly collimated. Lada (1985) presented a histogram of the collimation factor for 26 outflows; this histogram is reproduced in Figure 11. This histogram indicates that most outflows have small collimation factors. One can test if geometrical effects alone might account for the distribution of collimation factors that are seen in Figure 11. If we assume that the outflows are intrinsically well collimated (with a collimation factor of 5) and randomly oriented in space, we derive the distribution indicated by the dashed line in Figure 11. It is evident that the outflows can not be intrinsically well

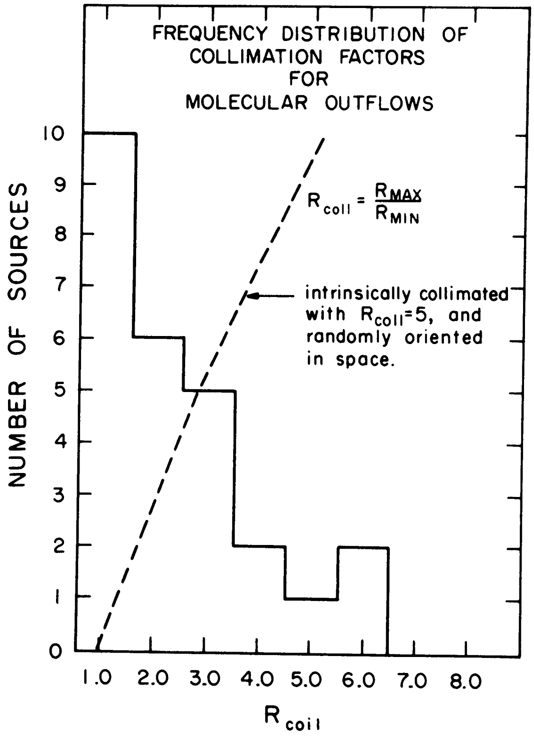

Figure 11. A histogram of the collimation factors for 26 outflows from Lada (1985). The dashed line shows the predicted distribution of collimation factors if the outflows are intrinsically well collimated and randomly oriented in space.

collimated and yet appear poorly collimated because of their orientation relative to the observer. It is also unlikely that resolution effects alone can account for the observed distribution, if the outflows are intrinsically well collimated. It seems most likely that the molecular outflows are intrinsically poorly collimated. This does not rule out the possibility that stellar winds are well collimated and, in fact, it may not be surprising that the expanding, highly supersonic molecular gas does not maintain a high degree of collimation.

4. FREQUENCY OF OCCURANCE

Molecular outflows are known to be associated with stellar objects with bolometric luminosities of 1 to 10^5 solar luminosities. Therefore, this energetic phenomenon can not be restricted to just massive stars but must be a common evolutionary phase of stars of a wide range of masses. From the tabulation of data by Lada (1985) and including the newly discovered outflows in several dark clouds (Myers et al. 1986; Hemeon-Heyer et al. 1986), a total of 59 molecular outflows are now known to exist within 1 Kpc of the sun. If the typical age for these outflows is $2\text{x}10^4$ years, then the rate of formation of outflows is $1.1\text{x}10^{-3}$ yr^{-1} Kpc^{-2}. This rate must then be the rate of formation of the progenitor stars of molecular outflows, if outflows occur only once in a star's lifetime. This rate can be compared with the estimates of the current star formation rate in the solar neighborhood as a function of mass (Mezger and Smith 1977; Miller and Scalo 1979). Such a comparison reveals that the rate of formation of all stars with masses greater than 1 solar mass is roughly the same as that for the progenitor stars of outflows. Therefore, not only must stars with a wide range of masses undergo a phase of energetic mass loss, but all stars with masses greater than one solar mass must go through this evolutionary phase to account for the observed number of molecular outflows near the sun.

Since the entire volume of space within 1 Kpc of the sun has not been searched, it is likely many more outflows will be discovered and stars of yet lower masses may be required to produce the observed number of outflows. One caution must be applied to the above analysis. The formation rate is based on a very poorly determined estimate of the outflow lifetime, if the lifetimes are much longer or shorter than the estimate of $2\text{x}10^4$ years, the rate of formation of outflows might be significantly overestimated or underestimated. Also, if stars have recurring mass loss events during their lifetime the rate of outflow formation will be reduced by the number of such episodes. These recurring events must be separated in time by more than 10^5 years to produce distinct signatures in the molecular cloud gas.

5. EFFECT ON MOLECULAR CLOUDS

The rapid rate of formation of these outflows when combined with the enormous energies that are involved, suggests that these outflows must be an important energy source within molecular clouds. Therefore, these outflows should have an important effect on evolution of the molecular clouds. Norman and Silk (1980) and Franco and Cox (1983) have suggested that these outflows may provide the dominate source of turbulent energy within molecular clouds and this feedback provides a self-regulating mechanism for the formation of stars. How dominant a role these outflows may play is still to be determined.

We can estimate the importance of the energy provided by molecular outflows using as an example the giant molecular cloud NGC2264. A comprehensive search for molecular outflows in this cloud has been recently completed by Margulis and Lada (1985); they found a total of 12 molecular outflows. If we use the nominal values summarized in §2.5 for the energetics of these outflows, we can estimate the energy input into this cloud to be 2×10^{33} ergs s^{-1}. The total kinetic energy within NGC2264 can be estimated from the mass of 2×10^{4} solar masses and velocity dispersion of 4 km s^{-1} measured by Crutcher, Hartkopf, and Giguere (1978). The total kinetic energy is estimated to be 2×10^{48} ergs. If the energy dissipation timescale is greater than 10^{7} years, then the energy input from outflows could have an dominant effect.

The timescale to dissipate the turbulent energy within molecular clouds is poorly known, although it is likely to be greater than the free-fall time scale of roughly 10^{6} years for GMCs. Scalo and Pumphrey (1982) have estimated the turbulent dissipation timescale to be approximately 7 times the free fall timescale. If their estimate is correct, then the outflows alone can provide the energy to replace that which is radiated away by the shocked gas produced in collisions of turbulent clumps within the clouds. This analysis assumes that the clouds are actually supported by their turbulent energy; alternatively, support by other means such as magnetic fields may instead dominate the support of clouds. If clouds are supported by their turbulent energy and if energy losses are replaced by the stellar outflows, then star formation may be self-regulating and the continued energy supply from newly formed stars could explain the longevity of molecular clouds.

6. STRUCTURE AND DYNAMICS OF OUTFLOWS

Since we know little about the actual mechanism that generates the stellar winds and collimates them into opposed jets, the structure and dynamics of the hypersonic molecular gas may provide important clues to the physics of this phenomenon. A number of studies have concentrated on the structure and dynamics of the outflow in Orion (Knapp _et al_ 1981; Kuiper, Zuckerman, and Rodriguez Kuiper 1981;

Erickson et al. 1982). However, this source is not well suited for such a study because of its small angular extent. The structure and kinematics of several larger molecular outflows have been recently studied in detail (Snell et al, 1984; Goldsmith et al. 1984; Snell and Schloerb 1985; Uchida et al. 1987; Moriarty-Schieven et al. 1986). The results of these studies will be discussed below.

Snell et al. (1984) analyzed the size of the high velocity emission and the position of the emission centroid as a function of velocity for several outflows. Two important results were found. The first, was that the apparent size of the high velocity emission remains relatively constant with velocity in all four outflows studied. Therefore, the outflows cannot be explosive, since one would expect the source size to increase with increasing velocity. Alternatively, the outflowing gas cannot be steadily decelerated away from its source, as the source size would be expected to increase with decreasing velocity. Secondly, in the two collimated outflows, NGC2071 and GL490, the centroid positions for the blueshifted and redshifted CO emission were found to be displaced from the outflow center.

Detailed observations of several well collimated bipolar outflows have also been made by Goldsmith et al. (1984). In their study the centroids of the high velocity emission in the B335 and L723 outflows were found to be displaced from the outflow center, similarily to that of NGC2071 and GL490. In fact, the map of B335 shows an absence of supersonic molecular gas near the source of the outflow (see Figure 12). The conclusions reached in both of these studies was that the

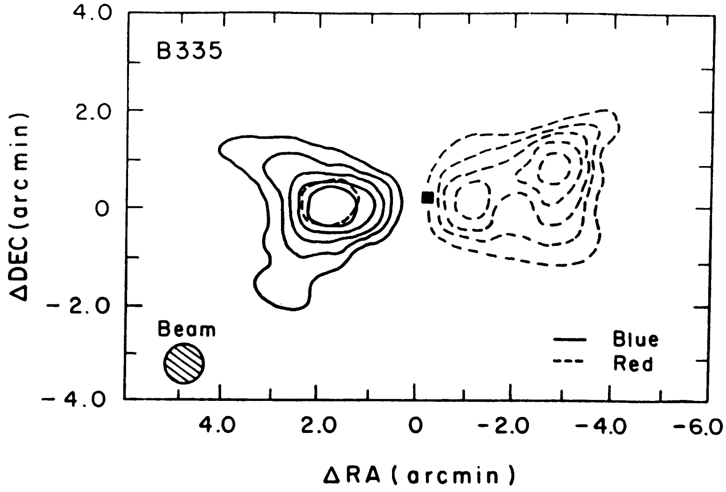

Figure 12. A contour map of the integrated intensity of the high velocity redshifted and blueshifted CO emission in the bipolar outflow in B335 from Goldsmith et al. (1984).

high velocity emission arises in ambient gas that has been swept-up into a slower moving shell which is now displaced from the outflow center. This expanding shell may surround a stellar wind-filled cavity within the molecular cloud analogous to the interstellar bubbles predicted to surround luminous stars (Castor, McCray, and Weaver 1975).

In most cases the angular resolution that is available is not sufficient to fully discern the structure of the outflowing molecular gas nor to determine if shell-like structures are present. The nearby dark cloud L1551 contains one of the most well-collimated and largest angular sized bipolar outflow known. Recent studies of L1551 by Snell and Schloerb (1985), Uchida et al. (1987), and Moriarty-Schieven et al. (1986) provide some relevant insights into the structure of the outflowing molecular gas.

The lunar occultation data of Snell and Schloerb (1985) permitted high resolution observations (~ 7 arcsec) of the blueshifted lobe of the outflow that was occulted by the moon. The data clearly showed that the lowest velocity outflowing gas is located at the periphery of the outflow, while the highest velocity gas was located at the center. Two models were suggested by Snell and Schloerb to explain this structure. First, the kinematics could be explained by viscous flow in which the gas at the periphery of the flow is slowed by interactions with the ambient gas. This model, unfortunately, does not give a satisfactory explanation as to why the bulk of the outflowing gas is located at the edge of the outflow. Alternatively, the data can be modelled as a shell of swept-up ambient gas which is moving both radially away from the stellar source as well as expanding. The highest velocity gas arises from the material on the front face of the shell that is expanding towards the observer. In this latter model the blueshifted lobe is 0.6 pc long, 0.12 pc in radius, and has a shell thickness of < 0.03 pc. The mean radial velocity of the molecular shell was estimated to be 12 km s^{-1} and the expansion velocity was estimated to be 4 km s^{-1}. The boundary of the shell was found to coincide with faint reflection nebulosity that has been interpreted by Snell et al. (1985) as scattered light from the stellar wind/molecular cloud interface and is supported by the polarization observations of Strom (1987). This model also has its failings, since the backside of the shell is not seen and must be assumed to be at the same velocity as the ambient gas and thus hidden from view.

One limitation of the Snell and Schloerb data was that increased angular resolution was obtained only along one cut through the outflow and in only the direction parallel to moon's motion. The data of Uchida et al. (1987) using the 45 m NRO telescope and Moriarty-Schieven et al. (1986) using the 14 m FCRAO telescope and image reconstruction techniques provide a more complete, high angular resolution view of the L1551 outflow. These observations have revealed a remarkable structure to the outflowing molecular gas. The spatial extent and location of the hypersonic emission is different for emission at different velocities. This is illustrated in

Figure 13 in which a contour map of a portion of the blueshifted hypersonic emission is shown at both the highest (left) and lowest (right) velocities (from Moriarty-Schieven *et al.* 1986). Gas at intermediate velocities are located between the high and low velocity emission. These data confirm the structure implied by the more limited data of Snell and Schloerb. A schematic diagram of a model for L1551 is shown in Figure 14 from Snell, Loren and Plambeck (1980) and illustrates the conclusion of Moriarty-Schieven *et al.* that the bulk of the expanding molecular gas is located in a shell-like structure.

One interesting aspect of the data shown in Figure 13 is that the highest velocity gas is not present near the stellar source, IRS-5. Such structure may be explained by the shell model proposed by Snell and Schloerb, or it may be explained by a model in which the material begins its acceleration near IRS-5 but does not reach its maximum velocity until much further away. Though clearly the data shown in Figure 13 show that the bulk of the expanding molecular material is located in a relatively thin shell, the distribution of the highest velocity gas is not so easily explained. The absence of emission from the backside of the proposed expanding shell suggests that the association of the highest velocity gas as arising from the frontside of the shell may be incorrect. Clearly, more complete observations are needed of the L1551 outflow as well as other outflows before any generalization can be made of the structure and kinematics of molecular outflows.

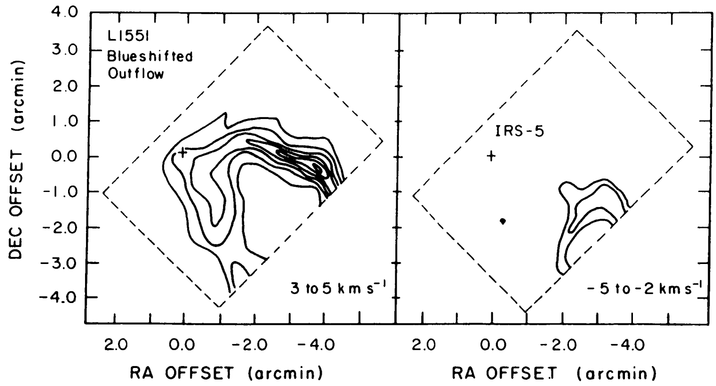

Figure 13. Contour maps of the blueshifted CO emission from a portion of the L1551 molecular outflow. Emission from the lowest velocity blueshifted gas (left) and the highest velocity blueshifted gas (right) are shown. These data are from Moriarty-Schieven *et al.* (1986) and was obtained with the FCRAO 14 m telescope using a maximum entropy reconstruction algorithm to obtain an angular resolution of 20 arcsec.

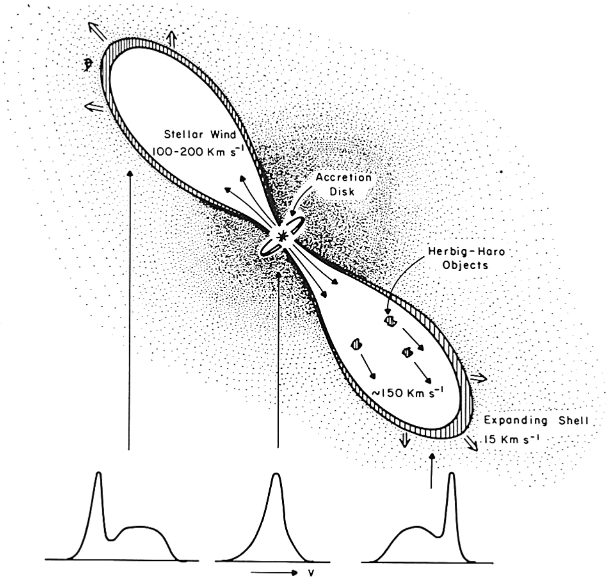

Figure 14. A schematic model of the molecular outflow in L1551 from Snell, Loren, and Plambeck (1980).

7. SUMMARY

It is obvious that the energetic outflows from young stellar objects are an important area of study. Their impact on stellar and molecular cloud evolution can not be fully appreciated until the origin of this phenomena, its energetics, and the nature of the progenitor stars are better understood. Observations that can detect the collimated stellar winds directly are essential to determine where, how, and why this phenomena occurs. In addition, better observations of the molecular outflows can provide invaluable information on the integrated energies and lifetimes of these outflows. Such data is essential to determine the impact these outflows have on their parent molecular clouds, the frequency of occurance of these outflows, and if molecular outflows really are a common evolutionary phase of stars of all masses. Before much more can be done to improve the lifetime estimates or energy estimates of outflows, it is essential to have a good model of the structure and kinematics of the high velocity molecular gas. With the many large millimeter telescopes and millimeter wavelength interferometers now in operation and with the use of spatial reconstruction techniques. the coming years will bring a new era in the study of this exciting and energetic event in the life history of stars.

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UCHIDA: Is the correction for the orientation, that the axis of the flow makes with the line-of-sight, taken into account in your histogram of elongations? Is there any correlation of elongation with galactic longitude? I would like to know if there is a tendency for the flow to be parallel to the large scale magnetic field.

SNELL: The histogram shown in Figure 11 does not take into account any correction for the orientation of the axis of the outflow relative to the observer. I have not looked for a correlation between the direction of the outflow axis and the galactic plane for the sample of outflows known. Sveral maps of outflows are shown in Bally and Lada (1983), oriented in galactic longitude and latitude, and these do not show any preferred orientation.

PUDRITZ: In your very pretty high resolution pictures of L1551, it appears that the higher velocity components have progressively less shell-like morphology. This is difficult to understand in a swept up shell model for CO emission,don't you think?

SNELL: The shell-like morphology persists at all velocities, although at higher velocities it is more compressed and therefore more difficult to see. Figure 13 illustrates this point. Certainly most of the mass of expanding gas comes from the periphery of the outflow, but the highest velocity gas may not necessarily come from gas on the front of the shell expanding toward us.

NORMAN: Dr. Downes argued yesterday that stellar winds could *not* provide the momentum input to support molecular clouds. You have shown the case of NGC 2264 where 12 bipolar flows embedded in a cloud can support the cloud structure. Which is correct and why?

SNELL: NGC 2264, studied by Margulis and Lada, is the first GMC to be surveyed in detail for outflows. I think these results indicate that outflows are an important energy source and may support molecular clouds. A similar conclusion can be reached if one assumes that all stars with masses greater than 1 solar mass go through this energetic evolutionary phase and deposit energies as indicated in Figure 8.

FUKUI: We have mapped CO wings in NGC 2071 and G1490 and found a very similar behaviour to what you observed in L1551: i.e., the lower velocity wings are more extended in space than the higher velocity wings and there are indications of acceleration of the outflow. Therefore that sort of velocity structure seems fairly common to these typical bipolar sources.

SNELL: These are very interesting results. It would be satisfying if a single model could be used to explain the structure and kinematics of all the bipolar outflows.

FUKUI: You mentioned that CO outflows have temperatures as low as 15 K. We measured NH_3 (1,1) and (2,2) spectra toward NGC 2071 and detected wings with temperatures as high as 40 K. This value strongly indicates that the molecular gas is heated by shocks (Takano *et al.*, Astron. Astrophys. 144, L20). Did you find any indication of high temperatures in CO?

SNELL: The study of outflows by Snell *et al.* (1984) found the temperature of high velocity CO to be similar to the ambient cloud temperature with no indication of any hotter gas present. It is possible that NH_3 is sensitive to the denser outflowing gas and that this gas is hotter than the gas observed in CO.