# II. The Physics and Chemistry of Molecular Outflows

# OBSERVATIONAL PROPERTIES OF MOLECULAR OUTFLOWS

RACHAEL PADMAN, STEPHEN BENCE AND JOHN RICHER
*Mullard Radio Astronomy Observatory*
*Cavendish Laboratory, Madingley Rd., Cambridge, CB3 0HE, ENGLAND*

**Abstract.** Molecular outflows are intimately related to the highly collimated Herbig–Haro jets emanating from young stars. In consequence, the usual dynamical timescale significantly underestimates the true age of an outflow. If we correct for this factor, and assume an intrinsic outflow speed similar to that of the underlying jet, we predict that molecular outflows should have an overall extent of several parsecs, in accordance with recent results. It seems likely therefore that outflows are a major source of interstellar turbulence, and have a profound impact on the process of star formation.

Whilst interpretation of jet-like outflows is relatively straightforward, the origins of shell-like outflows, such as that from L 1551–IRS5, are less obvious. We discuss the current observational status of both types of flow, and hypothesize an evolutionary connection between them. A large and well-defined outflow sample is urgently required, to permit the establishment of an age-sequence; such a sample would also provide the basis for a proper investigation of outflow energetics and interaction with the ISM.

## 1. Introduction

What is a molecular outflow? Until moderately recently the words suggested sources like the L 1551–IRS5 outflow, in which CO and other low-excitation species are observed in a pair of oppositely-directed and poorly-collimated "lobes", symmetrically located about an embedded YSO. It is now clear that molecular outflows are usually accompanied by many other phenomena, such as Herbig-Haro jets, radio free-free jets and even $H_2O$ masers. In this review we restrict attention primarily to the phenomenon as origi-

*B. Reipurth and C. Bertout (eds.), Herbig–Haro Flows and the Birth of Low Mass Stars,* 123–140.

nally understood. For the most part we will discuss the kinematics of the low-excitation molecular component of the gas, as traced by single-dish CO observations in the mm and submm wavebands. Fortunately, the interstellar chemistry of CO is quite simple, and the CO/$H_2$ abundance can thus be assumed to be constant for all values of extinction greater than about unity. On the other hand, instrumental resolution is generally not better than about 1000 AU, and we are perforce restricted to relatively large scale phenomena. Interferometer observations, such as those from the Plateau de Bure, are discussed by Guilloteau et al. elsewhere in this volume.

We also need to decide what is meant by "observational properties", and in particular whether to concentrate on individual outflows or on ensemble properties, such as the statistics of lobe length, maximum observed velocity, mechanical luminosity and thrust. Our approach here is to use individual outflows as examples, but to emphasize the role of ensemble properties in constraining the theoretical models.

It is not possible in a paper of this length to give a comprehensive review of all of the relevant observations. We hope we might be forgiven for illustrating our main points with examples drawn from our own observations and those of our collaborators. For an extremely comprehensive and up to date review of the field the reader is referred to the 1996 Annual Reviews article by Bachiller [1].

## 2. Properties of individual outflows

### 2.1. L1551–IRS5 AS AN ARCHETYPE?

As already noted, the "archetypal" outflow is that from L 1551–IRS5 [2]. The CO in this source is poorly collimated (the length to width ratio is only about 3). A Herbig–Haro jet emanates from the source (see Fridlund, this volume), and there are several Herbig–Haro objects, amongst them HH 28 and HH 29. The source itself is a 30 $L_\odot$ YSO [3], which is moderately deeply embedded: it is surrounded by a dust core which is just optically thick in $C^{17}O$ $2 \rightarrow 1$ [4].

At higher resolutions the CO gas is observed to lie in an open shell, with the source, IRS5, lying just at the apex [5] [6]. There is little evidence for a more collimated component to the outflow, although a number of "hotspots" suggest a current interaction with an invisible jet (which would have to be somewhat misaligned with the current axis of the outflow, as given by the Herbig–Haro jet from IRS5).

In about 1990 it was discovered that several outflow sources showed distinctly jet-like structures (particularly at high radial velocity offsets). Classic examples of these molecular jets can be seen in NGC2024 [7][8], L1448 [9], Orion South [10] and VLA 1623 [11]. Several lines of evidence

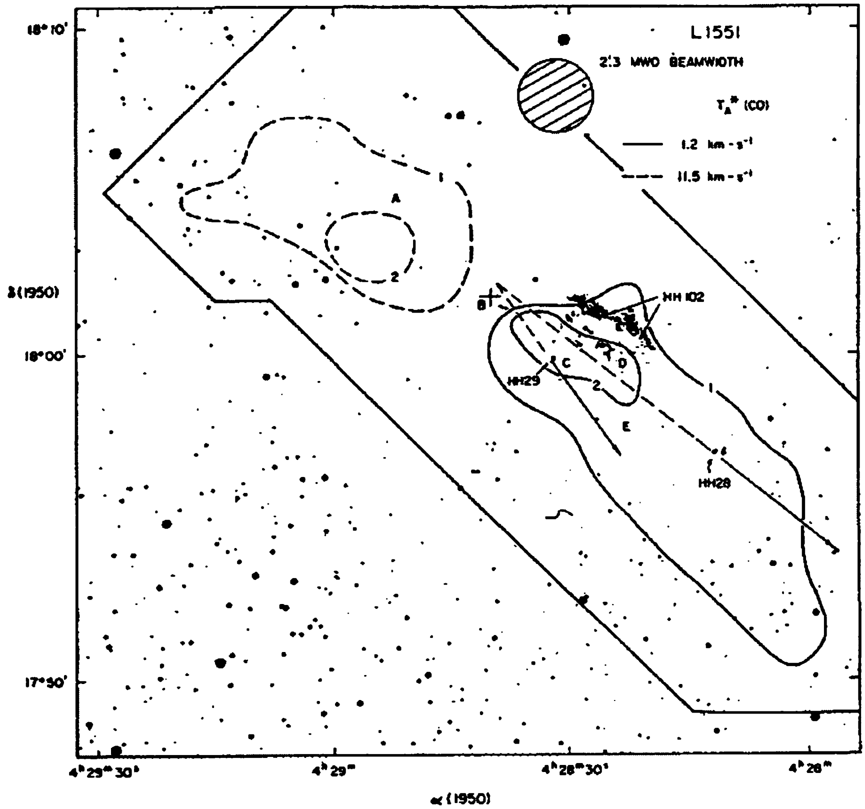

*Figure 1.* CO 1–0 in L 1551 (from Snell *et al.* 1980 [2])

suggest that the CO emitting gas in these sources consists of ambient cloud material swept-up by an underlying, and mostly invisible, jet:

- The collimation increases monotonically with radial velocity offset, whereas the apparent mass *decreases*, suggestive of an entrainment process.
- Most such sources show associated $H_2$ v=1-0 S(1) jets and bowshocks coincident with the most highly collimated CO (see, e.g. [8][12][13]).
- A few of these sources also show strong SiO emission, which is thought to be due to grain sputtering in shocks [14].
- Characteristic bow shock structures are associated with the ends of the jets, as deduced from the 3-dimensional spatial-velocity structure [15].
- The mass of the outflowing molecular gas is comparable with that deduced for the lobes in the absence of outflow, and is much greater

than could have been transported in the jet (assuming canonical mass loss rates and lifetimes).

Although interaction with an underlying high-velocity jet appears to be a good working hypothesis for the origin of the high-velocity CO emission in these sources, there are still many unresolved issues. For example, there is evidence that the jet varies both in strength and in direction (see, *e.g.* [15][16]). While this is undoubtedly reflected in the structures visible in CO, it does not seem that CO observations can elucidate this behaviour except indirectly. The CO observations are of much more direct relevance to the issue of how the ambient gas is entrained in the jet. It is certainly not clear yet (to observers!) whether this takes place at the head of the jet ('prompt' entrainment, [17]), along the sides of the jet ('lateral' or 'steady-state' entrainment, [18][19]) or at internal working surfaces [20]. Probably all three operate, and we would like to understand when each is important.

### 2.2. RNO 43: A JET-LIKE OUTFLOW

The outflow associated with RNO 43 [15] illustrates many of these phenomena. A very highly collimated CO 'jet' is associated with the inner parsec of the outflow, and is also seen in $H_2$ S(1) emission [21]. The overall extent of RNO 43 is of order 5 parsecs, and characteristic bow shock signatures are seen at each of the high-integrated-intensity "blobs" near the extremities of the source. The location and radial velocities of these blobs can be fitted to the surface of a cone of opening angle approximately 15°. It appears that the CO observations can be well fitted by assuming the CO to be entrained in an episodic and wandering underlying jet.

The axis of the RNO 43 outflow lies very close to the plane of the sky, and motions along the jet therefore have only a small radial component of velocity. Using simple symmetry properties, we can thus determine the 'longitudinal' and 'transverse' velocity distributions independently. The relative magnitudes of forward and transverse momenta provide useful constraints on models of outflow acceleration [25][26][27][28][29] (see also paper by Wilkin in this volume).

Of course, not all outflows are jet-like. Ironically, the intense interest in molecular jets has meant that the rest have been somewhat overlooked. Outflows like that from L 1551–IRS5 itself [2], and from the RNO 91 source in the L43 dark cloud [30], are completely different in structure. The molecular gas in both sources appears to lie in an open shell, with the source at the apex. It is probable that this is an evolutionary effect, with the shell-like outflows being older than the jet-like sources. But there has been no serious statistical study of this possibility, and it is also possible that simple environmental effects are responsible for the differences.

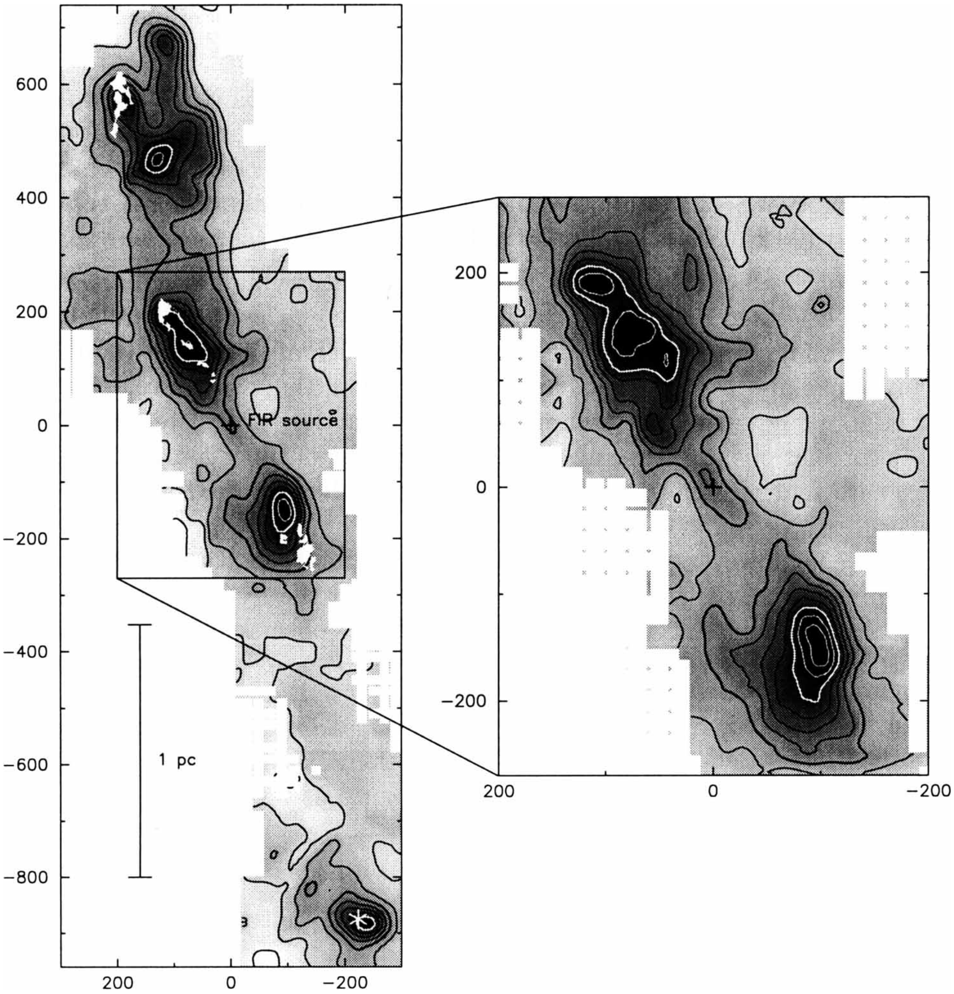

*Figure 2.* CO 2–1 integrated intensity in the RNO 43 outflow (adapted from Bence *et al.* 1996). The optical H–H objects observed by Mundt *et al.* (1987; [22]) and Reipurth (1991; [23]) are overlaid on the CO map, and the position of HH 179 (Reipurth, private communication; see also Reipurth *et al.* [24]) is indicated with a star. Offsets in both R.A. and Dec. are in arcseconds from the FIR source at $\alpha = 05^h29^m30^s.6$, $\delta = +12°47'35''$

## 3. Properties of the ensemble

### 3.1. STATISTICS

Lada [31] used early observations to plot the correlation between the luminosity of the central sources and the thrust and luminosity in the outflowing molecular gas. The correlation has now been re-examined and applied to a larger sample of sources [32][33], using the total source luminosity $L_{\rm bol}$

instead of $L_*$ and applying a consistent correction for the inclination factor. The newer results confirm two important points:

- The momentum supply rate to the CO-emitting gas (the thrust, $F_{\rm CO}$) is typically 100 times *larger* than that available in radiation from the central source ($L_*/c$).
- The mechanical luminosity in the CO-emitting gas, $L_{\rm CO}$ is typically 10 to 100 times *less* than the stellar luminosity ($L_*$).

Given the very large thrust, it is clear that the outflowing molecular gas can not be accelerated directly by radiation pressure — the opacity required is very much higher than we observe. But since much of the stellar luminosity is probably due to accretion, and knowing that the typical velocity of a jet is about equal to the escape velocity from the (proto)stellar surface, these correlations are strongly suggestive that the outflow is driven by some (magneto)hydrodynamic mechanism operating deep in the star's potential well.

There is, however, one major caveat to this interpretation. Calculations of luminosity and thrust have traditionally used the dynamical timescale, $\tau_{\rm dyn}$ as an estimate of the age when converting observed energy and momentum to supply rates:

$$\begin{aligned} L_{\rm CO} &= \frac{1/2 \int_{-\infty}^{\infty} v^2 M(v)\, dv}{\tau_{\rm dyn}}; \\ F_{\rm CO} &= \frac{\int_{-\infty}^{\infty} |v| M(v)\, dv}{\tau_{\rm dyn}}; \end{aligned}$$

where $M(v)$ is the total gas mass per unit velocity interval, and

$$\tau_{\rm dyn} = \frac{R_{\rm max}}{V_{\rm max}}, \qquad (1)$$

$R_{\rm max}$ is the maximum observed extent of the outflow, and $V_{\rm max}$ is its maximum observed velocity (in CO). Typically, $\tau_{\rm dyn}$ turns out to have a value less than a few $\times 10^4$ years.

On the other hand, Parker *et al.* [34] and Fukui *et al.* [35] both deduced statistical lifetimes for outflows a factor of ten higher than the dynamical times. Parker *et al.* found that over 75% of IRAS sources embedded in Lynds class VI dark clouds had associated outflows. Assuming that these IRAS sources would go on to become T-Tauri stars, and would appear as visible objects at an age of around 200 000 years, then *both* (a) more than 75% of embedded sources have outflows at some time, *and* (b), in those, outflow persists for more than 75% of the embedded lifetime. Fukui *et al.* used similar arguments to deduce the lifetime of outflows associated with visible T-Tauri stars, assuming an age of about 3 million years for the stars. The average *age* of these sources should then be just half their statistical lifetime, which for most sources is still much greater than the (observed) dynamical time.

Parker *et al.* did not correct for background sources, which were estimated to be up to 50% of the total near the Galactic plane, and the actual fraction of embedded sources with outflows must therefore be higher than 75%. Bontemps *et al.* [33] detected CO outflow in 80% of 45 class 0 and class I sources in a more heterogeneous sample. Outflow from YSOs therefore *must* persist for almost the entire duration of the embedded phase (although these statistics say nothing about whether it carries on into the class II and class III stages also).

### 3.2. IMPLICATIONS OF JET-DRIVEN MODELS

Arguments such as these show that the dynamical lifetime is most definitely not the *age* of the source. What is it then? Is it useful at all?

As defined, $\tau_{\rm dyn}$ depends both on the extent of the outflow and on the observed velocity. Both are subject to quite severe selection effects, depending on the sensitivity of the available instruments. Although we tend preferentially to see outflows with short dynamical times (i.e. those with the highest velocities), this cannot explain the discrepancy between dynamical time and statistical age in samples selected for some property *not* involving outflow.

In fact, in the "swept-up cloud" model, there is no reason to suppose that the molecular material should be moving at anything like the speed of the underlying jet. In the early stages of the outflow, where the jet is confined within the dense inner regions of the cloud core, we expect it to be underdense with respect to the quiescent cloud material. The rate of advance of the head of the jet, and also the highest longitudinal velocities in the swept-up gas, will therefore be limited by the momentum supply rate to the displaced quiescent material, and will be much less than the actual jet speed. In the outer regions of the cloud it is more likely that the jet will be ballistic, and both the rate of advance of the bow shock and the highest velocities in the molecular gas will approximate the jet speed. The dynamical time clearly depends on the time history of both these quantities, and therefore on the total run of densities in the cloud between the source and the present bow shock position [8].

It is interesting to note that neither observers nor theorists have got into the same tangle with optical jets. The reason appears to be that the dynamical timescale of those sources is *so* short (given the observed velocities of several hundred km/s and the relatively short jets) that it has never been remotely feasible that $\tau_{\rm dyn}$ could represent the age [22]. There just aren't enough T-Tauri stars in the sky! Clearly in this case $\tau_{\rm dyn}$ is just the time taken for the material in the jet to propagate from the source to the observation position. On the other hand, this might have been used to *predict* that optical jets should have very much larger extents than they were thought to have, until very recently. The discovery in 1994 of parsec scale jets, by Bally & Devine [16], should not have been a surprise....

The same argument applies to molecular outflows. A jet moving at 200 km/s will travel 20 pc in $10^5$ years. It would thus not be surprising to see outflows on this scale. In a series of recent observations using the QUARRY array receiver on the FCRAO 14-m telescope, Bence *et al.* (in preparation) have identified at least two very large scale outflows (Figures 3–6), from sources in the Parker *et al.* sample. Thus, of the handful of sources from the Parker *et al.* sample examined closely so far, both the L 1262 and L 588 outflows extend to more than 2 parsecs. RNO 43 (already mentioned) is at least 5 parsecs long. Large scale outflows are not rare.

### 3.3. IMPLICATIONS OF LARGE SCALE OUTFLOWS

The predicted scale size for outflows (up to 20 parsecs) is very much larger than that of the typical dark clouds from which they emanate. Even if the average scale size is only a few parsecs, the outflows still extend well beyond the visible cloud boundaries. In practical terms, if the opening angle of outflows is not too small, then a star-forming molecular cloud will feel the effects of the outflows originating within it throughout most of its volume.

One long-standing problem in star-formation and ISM theory is the origin of turbulence. When observed in CO and other abundant species, most molecular clouds have highly superthermal line widths. Since most clouds are also in virial equilibrium [37], this implies that turbulent motions (whether purely hydrodynamic or Alfvenic in character) dominate the cloud energetics. This turbulence must in turn largely regulate the star formation rate and efficiency. While there have been several large scale observational studies aimed at characterizing the turbulence (see, e.g. [38]), and a great deal of related theoretical work (see, e.g. [39]), the actual energy sources have not yet clearly been identified.

Norman & Silk [40] envisaged that winds from T-Tauri stars were responsible for the turbulence observed in molecular clouds, but this idea lost popularity with the discovery of molecular outflows. Outflows themselves have been seen as a possible source of turbulence ever since their discovery [41][42][43], but the interpretation has been complicated by the relatively small scale of outflows, apparently measuring a few tenths of a parsec at most. It was not clear how they could then affect more diffuse clouds on

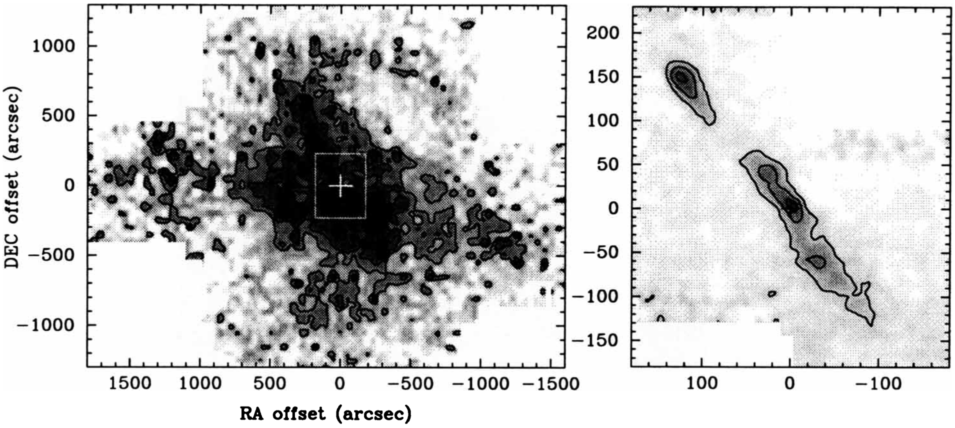

*Figure 3.* Integrated intensity maps of the L 1262 molecular cloud, in CO 1–0 (left; FCRAO) and CO 3-2 (right; JCMT). Channel maps of the CO 1–0 emission (not shown here) clearly show that most of the integrated intensity is due to local line broadening associated with outflowing gas, albeit with relatively small velocity offsets.

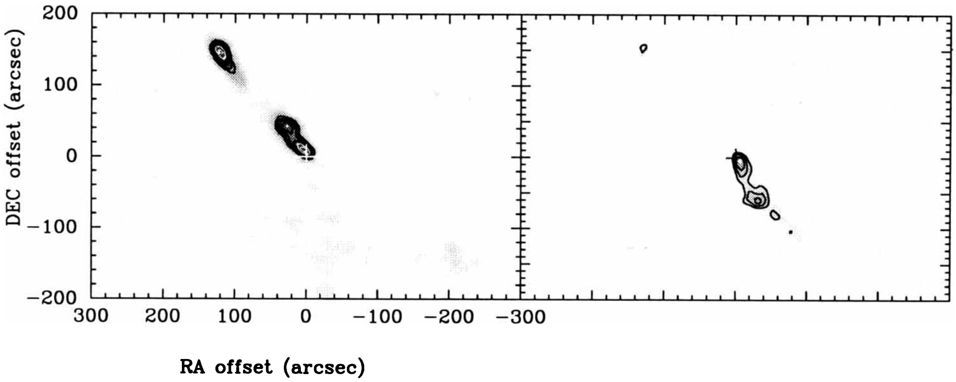

*Figure 4.* CO 3–2 blue- (left) and red- (right) shifted emission in L 1262

much larger scales.

This was partially resolved in 1994 by Chernin & Masson [46]. They noted that in HH 34 and HH 1-2 the momentum available in the optical jet far exceeded that which could be traced in the molecular medium, and deduced that the jet was depositing much of its momentum into the more diffuse ISM. Very strong support for this idea comes from the beautiful observations of very large scale optical jets — see the review by Bally & Devine, in this volume. Our new observations confirm that *molecular* outflows may well also inject significant turbulence into the more diffuse

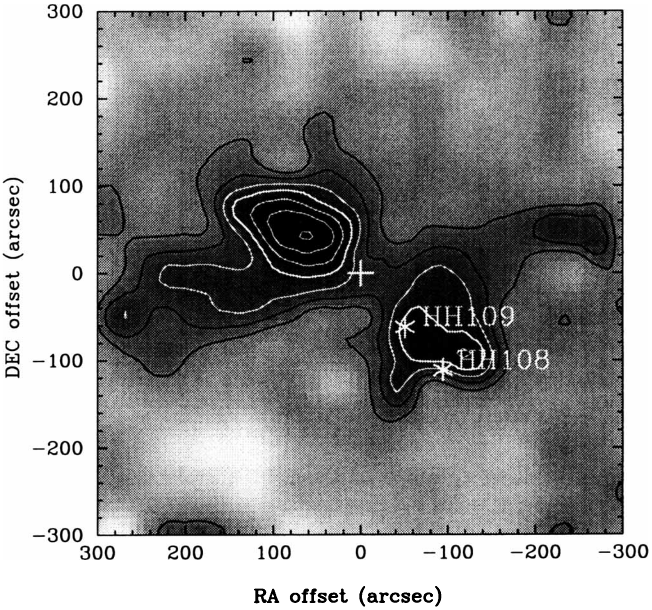

*Figure 5.* CO 1–0 integrated intensity in the inner regions of L 588, as observed at FCRAO using QUARRY. The line wings are very broad in this source, so that the integrated intensity is completely dominated by outflow. Two Herbig–Haro objects [36] are shown in the blue-shifted lobe of the CO outflow; the position of the IRAS source 18331-0035 is indicated with a cross.

ISM, although we have not yet managed to produce good numbers for the energy and mass loss rates at large scales — this is complicated by considerations of UV dissociation (see below).

In the cases we have observed in detail, we see that the orderly structure of the inner, collimated, outflow apparently breaks down in the outer regions, perhaps as a result of Rayleigh-Taylor and other instabilities affecting an overdense jet propagating in the diffuse ISM [44]. Furthermore, the size scales here are much larger than the typical separation of YSOs in an active star forming region such as Taurus-Auriga. Even with modest collimation, the "volume-filling factor" may well approach unity or greater, in which case we would expect frequent cases of outflows criss-crossing and interacting with each other, as observed for optical jets in NGC 1333 [45]. The situation is thus not so different from that suggested by Norman & Silk, with the only real departure being the substitution of collimated outflows for isotropic winds.

The second issue raised by the discovery of large-scale outflows is the survival of the molecular gas at very low visual extinctions. Again, this should come as no surprise — the L 1551 discovery paper of Snell *et al.* [2]

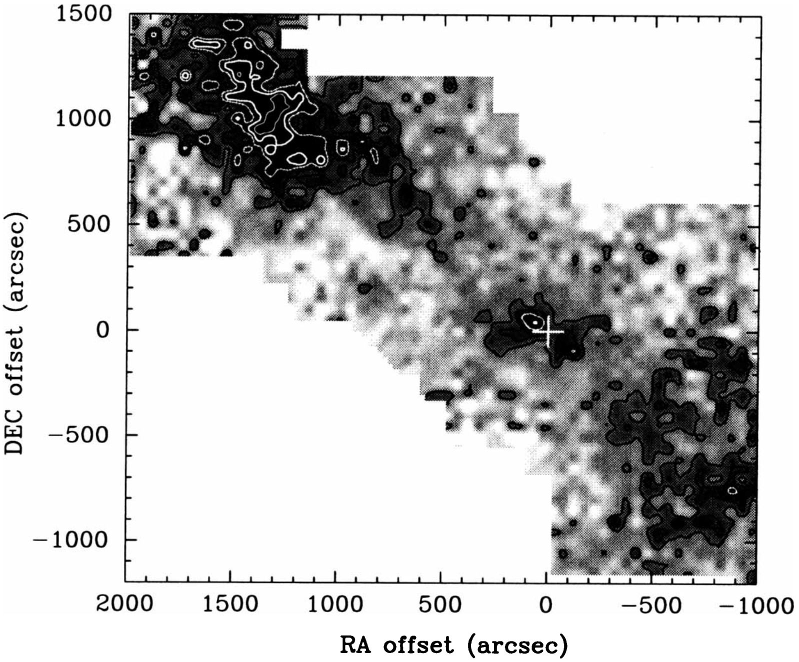

*Figure 6.* CO 1-0 integrated intensity in the environs of L 588. Note the fragmented emission to the NE and SW of the source, aligned with the inner outflow. Spectra taken in these two regions have the same radial velocity offset as those in the lobes of the inner outflow. The map is approximately 1 degree square.

presents an overlay of the CO outflow on the POSS plate, and background stars are clearly visible in the outer regions (see Figure 1). The L 1551–IRS5 outflow extends well beyond the L 1551 dark cloud itself. Standard theory (e.g. van Dishoeck & Black [47]) suggests that CO will be photo-dissociated on a time scale of order 50 000 years in a standard interstellar UV field ($G/G_0 = 1$), and proportionately faster as the UV intensity increases. We would therefore expect [CO]/([H] + [H2]) to be substantially reduced in the outer regions of the outflow. This may help to explain why large-scale outflows have not been discovered previously, and why many of the largest outflows already known are strongly asymmetric (see, e.g., the L 43–RNO 91 outflow presented by Bence *et al.* [48].) The *state* of the extended CO is not yet well understood, and observations of higher-J CO transitions are required so that we can estimate the temperature and the density.

Of course, the outflows do eject dust from the cloud core, as well as gas. The sky survey plates show dusty filaments around the CO shell in L 43, and in several other sources too, and the presence of hot dust is confirmed by the IRAS 60 and 100 $\mu$m images. But as the swept up material expands away from the cloud the dust rapidly becomes too diffuse to be visible, or to provide any shielding for the CO.

The discovery of large scale outflows, and the doubt this casts on the use of traditional dynamical timescale as a measure of age, implies that we should now be very curious about the origin of the correlation between $F_{\rm CO}$ and $L_*$ or $L_{\rm bol}$. If the dynamical timescale really bears no resemblance to the true age, why are these correlations so good?

A partial answer has been provided by Masson & Chernin [26], who re-plotted Cabrit & Bertouts' 6 cm fluxes for outflow sources [32] as a function of $P_{\rm CO}$ rather than as $F_{\rm CO}$ — which is effectively the same as assuming a constant age for all sources. The correlation is noticeably improved. Of course, this would not have been possible had it already been very good — the improvement shows that the correlation holds *despite* an erroneous attribution of source age, not *because* of it.[1]

Finally, we note that we have said nothing at all yet about the supposed "$v \propto r$" law for outflows. It has been suggested by several authors [29][49] that outflows obey a Hubble-like law, with the highest radial velocities being observed furthest from the source. Such a correlation implies velocity sorting associated with an explosive, or very rapid, origin for outflows or outflow episodes. This is hard to understand in the context of a jet-driven model, where the observed material has been accelerated *in situ*, rather than originating at the source.

Our own observations, and our interpretation of others', suggest that for many sources such a law does apply *locally*, at particular bow shocks. That is, as predicted by most theoretical models of bow shocks, the velocity dispersion peaks at the bow shock and falls behind it (towards the source) until it has the same value as that of the quiescent cloud. For small or incompletely-mapped sources, where only the most recent outflow episode is visible, this may well masquerade as a more global phenomenon. But there is little evidence in our data for any global "Hubble-law" in sources such as NGC 2024 [8]. This source appears already to have undergone multiple outflow episodes, as evidenced by the presence of several bow shock like features in the position-velocity diagram; the maximum velocity is essentially constant over at least 75% of the outflow extent.

---

[1] Insofar as it now compares a time-integrated property ($P_{\rm CO}$) with a current value ($S_{6\,\rm cm}$), the new plot is less aesthetically pleasing, and it would clearly be desirable to find a better measure of $F_{\rm CO}$, either by using more accurate values of $\tau_{\rm dyn}$ or, preferably, by using an instantaneous measure such as the estimate developed in [33].

## 4. Outflow evolution: where did L 43 come from?

It is often said that "collimation decreases with age". Given the uncertainty attached to the use of $\tau_{\rm dyn}$ as an age indicator, this has to be taken with a pinch of salt. The cynic might well rewrite the original statement as "the highest CO velocities are observed in the most collimated sources", which of itself would not be too surprising. In fact the personal bias of at least one of the current authors is that the best indicator of age is *size* — which is the same as saying that we should assume that all outflows have the same maximum velocity. At least in most models size increases monotonically with age, whereas $\tau_{\rm dyn}$ itself may well decrease in periods of activity.

At any rate, there is little doubt that the recently discovered (small) outflows in L 1527 [50] and TMC 1/TMC 1A [51] are quite young, as are those presented by Ohashi *et al.* [52]. Yet all of these sources have a characteristic butterfly shape, closely related to the ogive-shaped shells at the base of the outflow in L 1448, as revealed by IRAM Plateau de Bure Interferometer maps [53]. Shepherd & Watsons' poster paper [54] shows a similar CO structure around a massive star, as observed at OVRO. So even sources which show highly-collimated CO at *high* velocities, show cavity structure at *low* velocities. Collimation is thus dependent on the velocity range chosen for the observation, and presumably on the sensitivity of the observation also.

The view which emerges is much less black and white than the one we are used to. If most sources show jet and shell structures simultaneously, then the perceived collimation may be largely a function of the relative intensity of the two structures. Sources such as L 1448 and NGC 2024, in which the jet is very bright at high velocities, appear to be highly collimated; as the jet weakens the limb-brightened cavity walls start to dominate, as in L 1551–IRS5 and L 43–RNO 91.

Still, the CO jets in L 1551 and L 43 are *very* weak (if they even exist), and the cavities relatively large. We hypothesize that both of these are relatively evolved sources, in which the outflow is perhaps a few hundred thousand years old. Then most of the material originally within the cavity would have been dispersed into the diffuse ISM, and any residual jet would propagate freely, without interacting with the medium, and hence without radiating significantly. Some support for this hypothesis is obtained from the recent observations of the extended optical jet in L 1551 (Bally & Devine, this volume), while L 43 shows evidence for a weak CO jet roughly aligned with the middle of the cavity.

Detailed observations of the L 43 outflow ([30][48]) show that the cavity is expanding slowly, with a speed of order 1–2 km/s. It is not clear whether this is just a coasting shell created during the jet's passage, or if the motion is sustained by the pressure of a high-pressure low-emissivity medium within the cavity (or by the ram pressure of a low-emissivity wide-angled wind from the star). To complicate matters further, this velocity is also close to the terminal velocity for a bubble of size equal to the scale height rising under buoyancy. Further observations will be required to distinguish between these several possibilities.

As noted by both Cabrit and Shu in comments during this meeting, if the outflows from L 43–RNO 91 and L 1551–IRS5 actually extend much further than shown in conventional CO maps, then the actual collimation of these sources is greater than thought up until now. In effect, the relatively large cavities may be just the base of a very large structure which scales with time in a self-similar way. One very nice observation which seems to support this idea is that of the jet and outflow in the southern dark cloud, Sandqvist 136. Bourke's CO map [55] and I-band image [56] appear to show a source intermediate in appearance between the jet-like sources and the cavity sources.

## 5. Conclusion

It is hard to draw many general conclusions beyond those already discussed. As *the* conclusion to the review, and as a way of bringing together a few nice observational results not dealt with in the rest of our review, we briefly discuss both the outstanding problems (from an observational perspective) and what we see as the major areas requiring further work.

### 5.1. OUTSTANDING PROBLEMS

Single-dish CO observations are unlikely to have much direct impact on our understanding of the origins and properties of the jets themselves. They are of much more use, however, when considering the interactions of the jets with the surrounding, initially quiescent, ISM. It seems to us that there are (at least) two areas which have not yet been sufficiently explored, and which may cast a good deal of light on this process.

First, a very large fraction of outflows show overlapping red- and blue-shifted emission on both sides of the source. For a simple source model, in which the CO-emitting gas flows radially out from the source within a cone of constant opening angle, this is generally taken as an indication that the outflow axis lies within the cone half-angle of the plane of the sky. For example, for a half-angle of 30°, then we would expect 50% of sources to show such overlapping red and blue emission from a single lobe, and another 13% to appear 'pole-on' [57].

In fact, most outflows have opening angles much less than 60° — the average is perhaps only half this — and we would thus expect fewer than

30% of sources to have overlapping red and blue lobes. Projection factors mean that the apparent opening angle is always more than the true angle, which again decreases the fraction expected to show this phenomenon. This can be summed up, somewhat tongue-in-cheek, as "All outflows are in the plane of the sky". [2] It may be that in fact this is just telling us not to ignore the transverse velocity dispersion in the outflow. In any case, this observation must be an important constraint on the jet-driven model.

Our second observation is that "All outflows are self-absorbed". Even before bipolar molecular outflow was first identified, it was known that most of the sources were deeply self-reversed in lines of CO [58][59][60]. At the time this was interpreted as arising from *inflow* onto a hotter core. It is now clear that self-absorption is a widespread phenomenon, and Narayanan & Walker [61] have presented some lovely work showing how this can be used to discriminate between outflow episodes in Cep A. Much more needs to be done to establish this very promising tool as a more general diagnostic of outflow structure.

### 5.2. FURTHER WORK

First, there is a pressing need for a complete, high-sensitivity, *sample*[3] with well-understood selection effects. There have been two serious attempts to date. Parker *et al.* [34] defined a complete sample of about 25 sources, but due to instrumental limitations were able to observe only half of these in CO (and those not completely, as the more recent discovery of very large scale structure quite clearly shows). More importantly, it was not possible to map even that many sources in submm continuum, so the class of most of the YSOs is not yet known. Bontemps *et al.* [33] observed a more heterogeneous sample of class 0 and class I sources, and found similar statistics. Both samples are fundamentally limited by being IRAS-selected, which means that many class 0 sources may have been missed. Fortunately, instrumental throughput is improving very rapidly, especially with the advent of array receivers, and unbiased surveys of useful samples should soon be feasible.

The sample needs to be large enough to yield the distribution of objects with central-source luminosity, and to permit the establishment of an *age-sequence*. It may be possible to use the properties of the central object as an independent dating mechanism, but one should, however, beware the risks of circular reference....

---

[2] It is not easy to deduce the inclination by independent means, and almost the only sources for which it can be done at all are those for which we have both proper motions and radial velocities for the associated optical jets.

[3] There are lots of catalogues — these are not the same thing at all.

It is strange, but true, that after many years the state of the outflowing gas (density, temperature, filling factor) is still not well known [15][62][63], although it is clear that much of it is warm (more than about 30 Kelvin), dense (more than about $10^9/\mathrm{m}^3$) and clumpy (of unknown filling factor). Partly this is because it has been too difficult to observe both the high-frequency high-J CO lines and the lower-frequency low-brightness isotopomeric lines with adequate sensitivity and at the same resolution in all lines. Again, thanks to instrumental advances, observations can be made orders of magnitude more quickly than hitherto. We really need to know how the CO excitation varies near bow shocks, along and away from the jet, and within the cavities of the more evolved sources. Recent ISO results [64] indicate the great potential of high-J CO observations in particular.

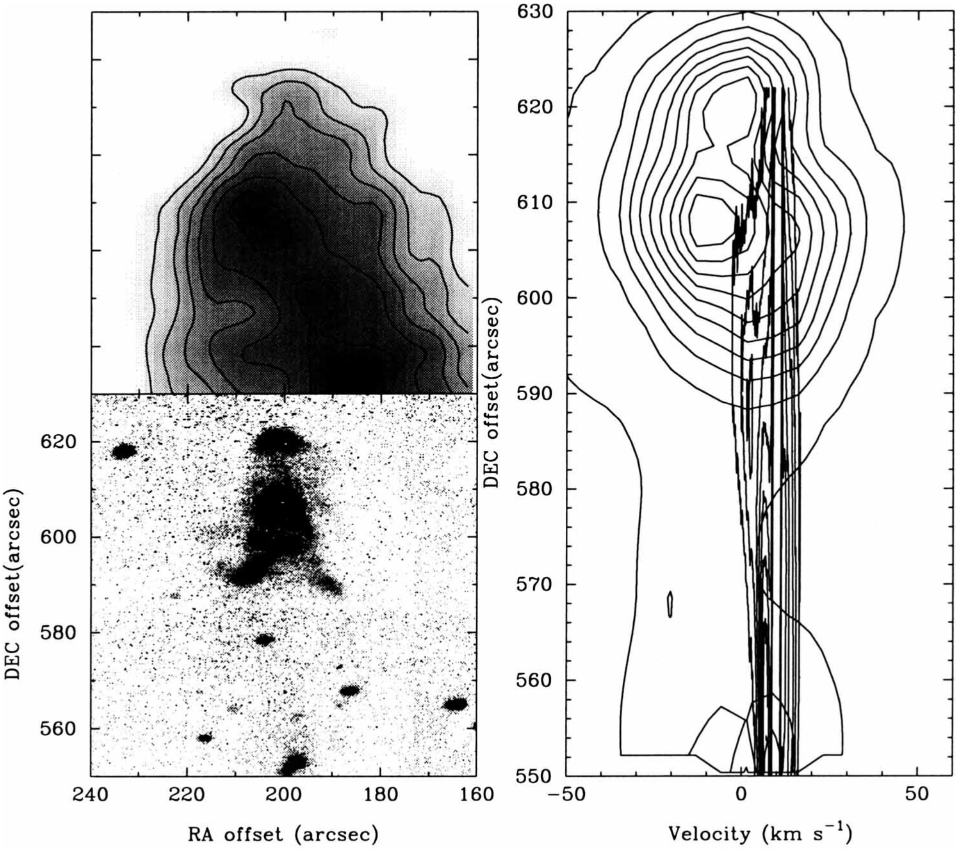

*Figure 7.* Images of the $H_2$ S(1) and CO 2–1 emission in RNO 43 (from Bence *et al.* [21]). We also show the overlaid position-velocity diagrams, where both datasets have been convolved to the same spatial resolution. The offset between the maximum velocities of the peaks in each species can be clearly seen.

Finally, we emphasize that molecular outflows are *not* distinct from the other outflow phenomena which together constitute the subject of this meeting. CO traces the low-excitation component of the gas merely, and any real understanding must involve a synthesis of observations of species with a wide range of excitation conditions. As a parting shot, we illustrate our point with an overlay of the position velocity diagrams of $H_2$ v=1-0 S(1) and CO emission in the N4 region of RNO 43 [21] (Figure 7). The emission from the two species is clearly different, but complementary. Presumably that from [SII], say, will be different again. Understanding the relationship between these plots is the key to an understanding of the outflow phenomenon in general.

**Acknowledgements:** Thanks to all our MRAO collaborators – particularly Adrian Russell, Nick Parker, Paul Scott, Richard Hills, Claire Chandler, Kate Isaak, Martina Wiedner and Richard Blundell. RP also thanks Colin Masson, for many scientific discussions, for his insight into the problems raised by molecular outflows, and especially for his generous hospitality during several visits to Pasadena and CfA.

## References

1. Bachiller, R. 1996. Ann. Rev. Astron. Astrophys. 34, 111
2. Snell, R. L., Loren, R. B. & Plambeck, R. L., 1980, ApJ 239, L17
3. Cohen, M,. Harvey, P.M., Schwartz, R.D. & Wilking, B.A. 1984. ApJ 278, 671
4. Fuller, G.A., Ladd, E.F., Padman, R., Myers, P.C.,& Adams, F.C. 1995. ApJ 454, 862
5. Moriarty-Schieven, G. H., Snell, R. L., Strom, S. E., Schloerb, F. P., Strom, K. M. & Grasdalen, G. L., 1987, ApJ 319, 742
6. Moriarty-Schieven, G.H. & Snell, R.L. 1988. ApJ 332, 364
7. Richer, J. S., Hills, R. E., Padman, R. & Russell, A. P. G., 1989, MNRAS 241, 231
8. Richer, J. S., Hills, R. E. & Padman, R., 1992. MNRAS 254, 525
9. Bachiller, R., Cernicharo, J., Martin-Pintado, J., Tafalla, M. & Lazareff, B., 1990, A&A 231, 174
10. Schmid-Burgk, J., Gusten, R., Mauersberger, R., Schulz, A. & Wilson, T. L., 1990. ApJ 362, L25
11. Andre, Ph., Martin-Pintado, J., Despois, D. & Montmerle, T., 1990, A&A 236, 180
12. Davis, C.J., Dent, W.R.F., Matthews, H.E., Aspin, C. & Lightfoot, J.F. 1994. MNRAS 266, 933
13. Bally, J., Lada, C.J. & Lane, A.P. 1993. ApJ 418, 322
14. Bachiller, R., Martin-Pintado, J. & Fuente, A. 1991. A&A 243, L21
15. Bence, S.J., Richer, J.S. & Padman, R. 1996. MNRAS 279, 866
16. Bally, J. & Devine, D. 1994, ApJ 428, L65
17. De Young, D.S., 1986, ApJ 307, 62
18. Stahler, S. 1994. ApJ 442, 616
19. Raga, A.C., Canto, J., Calvet, N., Rodriguez, L.F. & Torrelles, J.M. 1993 A&A 276, 539
20. Raga, A.C. & Cabrit, S. 1993. A&A 278, 267
21. Bence, S.J., Richer, J.S. & Wright, G.S. 1997. MNRAS (submitted)
22. Mundt, R., Brugel, E. W. & Buhrke T., 1987. ApJ 319, 275
23. Reipurth, B. 1991. in *The Physics of Star Formation and Early Stellar Evolution.*,

ed C.J. Lada & N.D. Kylafis. NATO ASI Series C vol 342, 497.

24. Reipurth, B., Bally, J. & Devine, D. 1997. Astron. J. (in press)
25. Chernin, L.M., Masson. C., Gouveia Dal Pino, E.M. & Benz, W. 1994. ApJ 426, 204
26. Masson, C. R. & Chernin, L. M., 1994. in *Clouds, Cores and Low Mass Stars*. ed D.P. Clemens & R. Barvainis. ASP Conf. Series. 65, 350
27. Chernin, L.M. & Masson, C.R. 1995. ApJ 455, 182
28. Wilkin, F.P. 1996. ApJ 459, L31
29. Lada, C.J & Fich, M. 1996. ApJ 459, 638
30. Bence, S.J., Padman, R., Isaak, K., Wiedner, M.C. & Wright, G.S. 1997. MNRAS (submitted)
31. Lada, C.J. 1985. Ann. Rev. Astron. Astrophys. 23, 267
32. Cabrit, S. & Bertout, C., 1992. A&A 261, 274
33. Bontemps, S., Andre, Ph., Terebey, S. & Cabrit, S. 1996. A&A 311, 858
34. Parker, N. D., Padman, R. & Scott, P. F., 1991, MNRAS 252, 442
35. Fukui, Y., Iwata, T., Mizuno, A., Bally, J. & Lane, A. P., 1993, in *Protostars and Planets III*, ed E.H.Levy & J.I.Lunine. Univ.Arizona Press, Tucson. p603
36. Reipurth, B., & Eiroa, C. 1992. A&A 256, L1
37. Larson, R.B. 1981. MNRAS 194, 809
38. Falgarone, E., Puget, J.-L. & Perault, M. 1992. A&A 257, 715
39. Falgarone, E. & Phillips, T.G. 1990. ApJ 359, 344
40. Norman, C. & Silk, J., 1980. ApJ 238, 158
41. Solomon, P.M., Huguenin, G.R. & Scoville, N.Z. 1981. ApJ 245, L19
42. Margulis, M. & Lada, C.J. 1986. ApJ 309, L87
43. Fukui, Y., Sugitani, K., Takaba, H., Iwata, T., Mizuno, A., Ogawa, H. & Kawabata, K. 1986. ApJ 311, L85
44. Stone, J.M., Xu, J. & Mundy, L.G. 1995. Nature, 377, 315
45. Bally, J., Devine, D. & Reipurth, B. 1996. ApJ 473, L48
46. Chernin, L.M. & Masson, C.R. 1995. ApJ 443, 181
47. van Dishoeck, E.F. & Black, J.H. 1988. ApJ 334, 771
48. Bence, S., Padman, R. & Isaak, K. 1997. in *Low Mass Star Formation from Infall to Outflow*, ed. F. Malbet & A. Castets, Poster Proc. IAU 182, 57
49. Wolf, G.A., Lada, C.J. & Bally, J. 1990. AJ 100, 1892
50. Zhou, S., Evans, N.J. & Wang, Y. 1996. ApJ 466, 296
51. Chandler, C.J., Terebey, S., Barsony, M., Moore, T.J. & Gautier, T.N. 1996. ApJ 471, 308
52. Ohashi, N., Hayashi, M., Kawabe, R. & Ishiguro, M. 1996. ApJ 466, 317.
53. Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P. & Martin-Pintado, J. 1995. A&A 299, 857
54. Shepherd, D. & Watson, A.M. 1997. in *Low Mass Star Formation from Infall to Outflow*, ed. F. Malbet & A. Castets, Poster Proc. IAU 182, 175
55. Bourke, T.L., Garay, G., Lehtinen, K.K., Kohnenkamp, I., Launhardt, R., Nyman, L.-A., May, J., Robinson, G. & Hyland, A.R. 1997. ApJ 476, 781
56. Bourke, T.L., Hyland, A.R., Robinson, G. & James, S.D. 1993. Proc. Astron. Soc. Australia 10, 236
57. Cabrit, S. & Bertout, C., 1990. ApJ 307, 313
58. Phillips, T.G., Huggins, P.J., Wannier, P.G. & Scoville, N.Z. 1979. ApJ 231, 720
59. Phillips, T.G., Knapp, G.R., Huggins, P.J., Werner, M.W., Wannier, P.G., Neugebauer, G. & Ennis, D. 1981. ApJ 245, 512
60. Loren, R.B., Plambeck, R.L., Davis, J.H. Snell, R.L. 1981. ApJ 245, 495
61. Narayanan, G. & Walker, C.K. 1996. ApJ 466, 844
62. Plambeck, R.L., Snell, R.L., & Loren, R.B. 1983. ApJ 266, 321
63. Wootten, A., Loren, R.B., Sandqvist, A., Friberg, P. & Hjalmarson, A. 1984. ApJ 279, 633
64. Liseau, R. *et al.* 1996. A&A 315, L181