Molecular outflows and 1000 AU structure of low mass YSO envelopes

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Abstract

We present the results of an observational study into the molecular outflows and small scale ($\sim$ 1000 AU) envelope structure of a sample of nine low mass young stellar objects (YSOs) in Taurus. The characteristics of the outflows are derived from ^{12}CO $J = 3-2$ mapping with the James Clerk Maxwell Telescope, while the envelopes are imaged in the HCO$^+$ 1–0, ^{13}CO 1–0 and C^{18}O 1–0 emission lines with the Owens Valley Millimeter Array. Using dust envelope continuum fluxes at 1 mm as the basis for an evolutionary ordering, a picture emerges in which the mass, extent, and collimation of outflows decreases over time as the envelopes become less massive, the opening angle of the outflow cavity increases, and mass accretion through the disk slows down. On 1000 AU scales the HCO$^+$ and ^{13}CO/C^{18}O emission in the envelope is closely related to the outflow cavity, often outlining the cavity walls. In addition, the envelopes are clumpy, and two sources appear surrounded by an incomplete ring or torus, 1500–3000 AU in radius. The role of the outflow in shaping the small scale molecular emission may be passive (creating a low–opacity pathway for heating radiation) rather than, or in addition to, active (compressing and shock–heating the material).

1. Introduction

The phenomenon of mass outflow is well established as an integral part of the process of star formation, and is expected to have a pronounced influence on the envelope out of which the star is forming (see e.g. Shu et al. 1993). Eventually, it may be responsible for reversing mass infall, and clearing the surroundings of the pre–main sequence object. Its driving mechanism is thought to be mass accretion from a circumstellar disk onto the protostar (cf. Königl & Ruden 1993), resulting in an intense stellar wind.

Although a general scenario for low mass star formation is accepted (Shu et al. 1993), and much has been learned during recent years from the study of a handful of "prototypical" YSOs, little is known about the details of the evolution during the embedded phase. Outflow characteristics have usually been derived for extended, massive flows, but these may not be typical for outflows in general (cf. Wu, Huang & He 1995). We are therefore carrying out a study of a well defined sample of thirteen low mass YSOs in the nearby star forming regions of Taurus and Serpens, tracing a broad range in size scales and physical parameters through interferometric and single dish (sub–) millimeter observations of molecules.

In this poster the relationship between the molecular outflow and small scale (< 1000 AU) structure in the circumstellar envelope will be investigated based on nine of our YSOs in Taurus (see also Hogerheijde et al. 1997b). Since all of these objects are located in the same environment, which is forming stars in only a limited range of masses ($0.4 - 0.8\ M_\odot$, Cohen & Kuhi 1979), the effects of evolution are maximized compared with those of initial conditions like temperature or mass. Our nine objects have been selected from the flux– and color–limited sample of Tamura et al. (1991) by their HCO$^+$ $J = 3-2$ emission, and are likely to be the objects with at least 0.01 $M_\odot$ of their primeval envelopes still present, i.e. relatively young.

2. Outflow characteristics: ^{12}CO $J = 3-2$

Evidence of outflow emission has been observed toward all sources of our sample (Terebey, Vogel & Myers 1989; Moriarty–Schieven et al. 1992), but only T Tau, L1551 IRS5 and L1527 have been studied in detail (Levreault 1988; Margulis & Snell 1989; Moriarty–Schieven & Wannier 1991; Frerking & Langer 1982; MacLeod et al. 1994). We have obtain $2' \times 2'$ maps in ^{12}CO 3–2 with the James Clerk Maxwell Telescope (JCMT)[1] toward the remaining six objects.

It is found that the outflow emission toward these six sources is confined to $\leq 1'$ ($\leq$ 10000 AU) from the driving sources, much less than the $2' - 10'$ found toward T Tau, L1551 IRS5 or L1527. Their masses are also smaller by an order of magnitude (see Table 1 for an overview of outflow characteristics). The outflows of our sources can be roughly divided in three morphological types: 1) extended (several arcmin) and massive (0.1–0.5 $M_\odot$) flows, with a clear bipolar structure (T Tau, L1551 IRS5, L1527); 2) small ($< 1'$), less massive ($< 0.1\ M_\odot$) flows, but well collimated and nicely mono– or bipolar (L1489 IRS, TMR–1, TMC–1A, TMC–1); 3) flows with an equally small extent and mass as (2), but lacking a clear mono– or bipolar structure (L1524 and L1535). In Fig. 1 an example of each of the three cases is given. It is noted here that, except for T Tau, all our sources are seen under an inclination of $60° - 90°$, i.e. nearly edge–on (Kenyon et al. 1993). Orientation therefore does not explain the different outflow shapes.

[1]The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research and the National Research Council of Canada.

Table 1: Outflow parameters [1]

Source	$M_{\rm flow}$ $M_\odot$	$L_{\rm kin}$ $L_\odot$
L1489 IRS	1.7×10^{-2}	1.1×10^{-1}
T Tau	2.0×10^{-1}	4.7×10^{-1}
L1524	3.3×10^{-2}	1.2×10^{-1}
L1551 IRS5	3.0×10^{-1}	2.9×10^{-1}
L1535	1.6×10^{-2}	4.7×10^{-3}
TMR–1	2.0×10^{-2}	9.3×10^{-3}
TMC–1A	1.4×10^{-2}	7.8×10^{-2}
L1527	2.0×10^{-1}	8.7×10^{-2}
TMC–1	1.9×10^{-2}	1.2×10^{-1}

[1] Using $L_{\rm kin} = MV^3/2R$ (Cabrit & Bertout 1990), where M is the total mass in the outflow, V the maximum red– and blueshifted velocity and R the linear extent of the flow.

3. Evolutionary ordering of molecular outflows

Irrespective of the details of protostellar collapse, the mass of the circumstellar envelope is expected to decrease with time. Hogerheijde et al. (1997a) used this consideration to devise an evolutionary ordering of the sources of the Taurus sample. The similar environment in which these objects have formed allows such a comparison. Mass estimates were obtained from the optically thin dust continuum flux at 1.1 mm (Moriarty–Schieven et al. 1994), after subtraction of the contribution of the circumstellar disks (see below). The fact that both the dust continuum and the observed HCO^+ line emission can be described by the same parameters indicates that temperature differences are not a major factor in the range of envelope fluxes. The excitation of HCO^+ is only weakly dependent on temperature. It is concluded that the envelope continuum flux is a useful basis for an evolutionary ordering.

In Fig. 2 the derived outflow kinetic luminosities are plotted against the envelope fluxes. Within the evolutionary ordering sketched above, time runs from right to left in the diagram. It can be seen that the outflow luminosity decreases with time. In addition, the three outflow "types" discerned in the previous section can also be seen to make up an evolutionary "sequence". This suggests that after an initial period of collimated, massive and extended outflow emission, YSOs evolve toward driving increasingly less massive, less extended and less well collimated outflows.

In many theoretical models of jets and outflows, mass accretion from the disk onto the star plays a crucial role. Two–thirds of our objects have detected continuum emission from these unresolved disks (see below). The outflow luminosities of the sources are plotted in Fig. 3 against the fluxes (and upper limits) of the disks. From the apparent correlation it is concluded that sources which have more massive and/or warmer, i.e. more actively accreting disks, drive more powerful outflows. Together with the correlation of Fig. 2, it is likely that the mass accretion rate decreases with time.

It is hypothesized that as the envelope mass de-

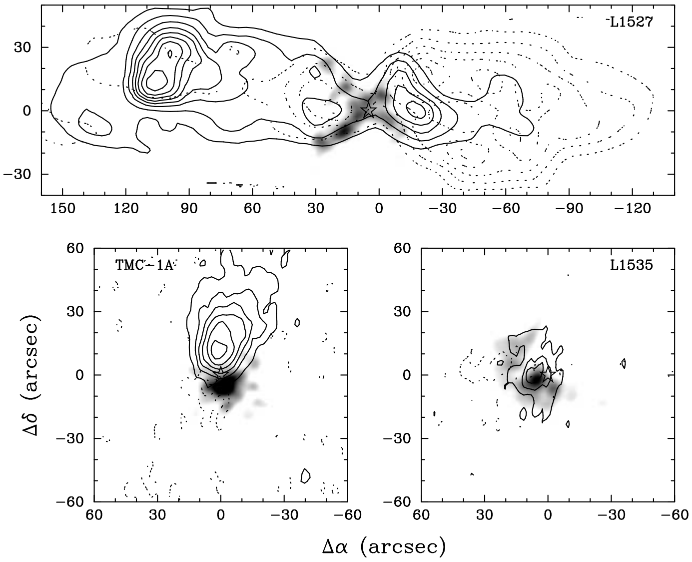

Fig. 1.— Examples of the three morphological "types" of outflows, respectively L1527, TMC–1A and L1535. Contours are integrated ^{12}CO 3–2 emission over the blue–shifted (solid) and red–shifted (dashed) lobes (Data for L1527 from MacLeod et al. 1994). The greyscale is the velocity integrated HCO^+ 1–0 emission as observed by OVRO. This compact molecular emission is seen to be closely connected to the outflow (cavity walls).

creases with time, less material is swept up by the wind from the star–disk system, which in itself may also grow more tenuous. This could explain why young protostars are found to be associated with well–collimated, extended and massive outflows, while older objects drive irregular, low mass flows. The material which was incorporated in the outflow in the early phases of the evolution may at these later stages have lost the excitation or column density required to be observable in e.g. ^{12}CO 3–2. A similar evolutionary scheme for molecular outflows was proposed by Saraceno et al. (1996) and Bontemps et al. (1996) on the basis of $L_{\rm kin}$ and $L_{\rm bol}$ or $F_{1.1\ \rm mm}$ of larger samples.

4. Small scale structure in the envelopes

Small scale emission is readily detected toward all sources, both in 89 and 109 GHz continuum and in HCO^+, ^{13}CO and $C^{18}O$ 1–0. Observations of these lines, and the continuum emission at these frequencies, have been obtained with the Owens Valley Millimeter Array (OVRO)[2] . In continuum emission, two–thirds of our sample is found to be associated with unresolved ($< 4''$) emission attributed to circumstellar accretion disks.

The spatial distribution of the small scale molecular emission is closely related to that of the outflows, out-

[2] The Owens Valley Millimeter Array is operated by the California Institute of Technology under funding from the U.S. National Science Foundation (#AST93–14079).

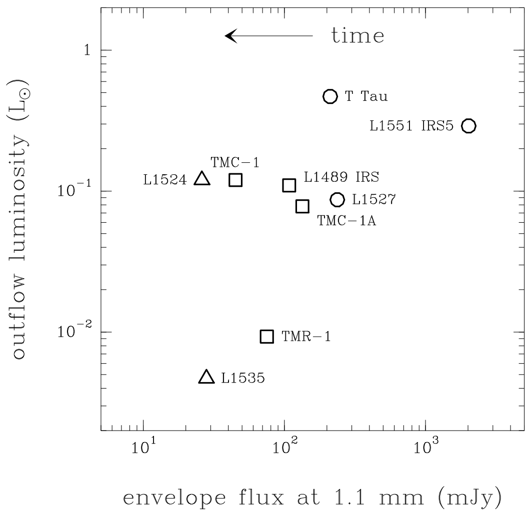

Fig. 2.— Outflow kinetic luminosity vs envelope flux at 1.1 mm of our sources. If the latter is used as an evolutionary tracer (see text), time is running from right to left in the diagram, and the kinetic luminosity is seen to decrease with time. Furthermore, the outflows develop from extended, massive and well collimated (circles), via smallish but still collimated (squares) to small and irregular (triangles).

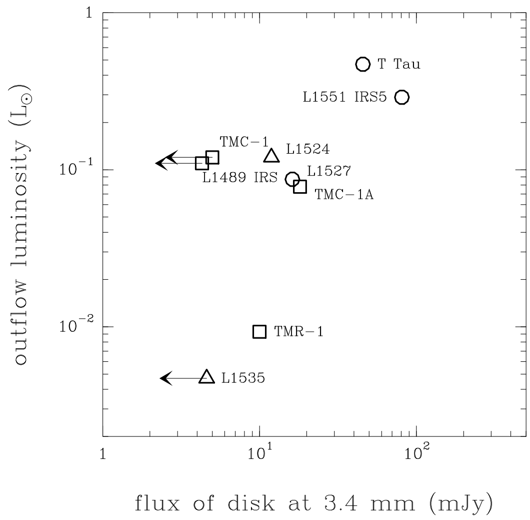

Fig. 3.— Outflow kinetic luminosity vs continuum flux of the circumstellar disks of our sources. The correlation between these quantities suggests that more actively accreting, and hence warmer or more massive disks drive more powerful outflows. The symbols denote the different outflow shapes, as in Fig. 2.

lining in many cases the walls of the outflow cavity as well as the dense equatorial planes of the envelope. In Fig. 1 a few examples are given. Compared to images at 2 μm of Hodapp (1995), the molecular emission is seen to avoid the low–opacity regions through which this scattered light can escape. The envelopes around our YSOs are clumpy on 1000 AU scales, and in two cases (L1535 and TMR–1) the objects appear to be surrounded by an (incomplete) ring or torus of 1500–3000 AU in radius, which are also visible as absorption 'lanes' at 2 μm (cf. Terebey et al. 1989).

The mass contained in these compact structures is 10%–70% of the inferred envelope dust mass, implying that a significant fraction of the continuum emission originates in the cavity walls. These may dominate the emission even when comprising only little of the total mass if their temperature is enhanced over that of the unperturbed envelope. The role of the outflow in heating the cavity walls may be active, i.e. through slow–moving shock waves, or more passive, by creating the possibility for heating radiation from the star–disk system to scatter into the envelope through the evacuated cavity (cf. Spaans et al. 1995).

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