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Jets and Outflows from Massive Protostars

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Abstract. Molecular outflows are found in most regions of massive star formation. However, evidence for highly collimated jets from massive protostars is still elusive. This paper briefly summarizes the observational status.

1. Introduction – Outflows and High Mass Star Formation

Mass outflow from young stellar objects is a ubiquitous phenomenon in star-forming regions (SFRs) and seems to commence in the earliest phases of protostellar development; see Bachiller (1996) and Churchwell (1999) for recent reviews and Shepherd & Churchwell (1996a) for a survey of 122 high mass SFRs, 90% of which exhibit evidence for outflow activity.

Many low mass protostars show highly collimated, jet-driven bipolar flows observable in atomic and ionic optical lines and in infrared- and millimeter-wavelength molecular emission. Outflows in high mass SFRs frequently have a bipolar morphology as well (Shepherd & Churchwell 1996b). However, evidence for the existence of highly collimated jets originating from bona fide massive protostars is presently sparse at best. Whether or not such jets exist may provide important information on the high mass star formation process itself, since in a variety of astrophysical settings the presence of a collimated jet implies an accretion disk at its origin (Livio 1999) and it is presently unclear whether massive stars form by accretion (involving a disk or not) or in other ways, such as coalescence of lower mass stars (Stahler et al. 2000; Bonnell et al. 1998). In this context it is important to mention the observation that in many cases the mass in the outflowing material is greater (by up to factors of a few) than any plausible value for the mass of the protostar driving it. This led Churchwell (1997) to conclude that infalling matter has to be diverted into the bipolar outflow. While the mechanism for this remains unclear, these observations seem to support an accretion scenario (Norberg & Maeder 2000). In the following we summarize the observational information on outflows and jets in high-mass SFRs.

2. Molecular Line Observations

The first evidence for high velocity molecular gas in high-mass SFRs came from observations of high velocity components in spectra of the 22 GHz water vapor (H_2O) maser transition, which in some regions, such as Orion-KL or W49 cover velocity ranges up to ± 200 km s^{-1} around the systemic velocity. Strelnitskii & Sunyaev (1973) were the first to propose mass outflow to explain the high velocity H_2O and this interpretation was confirmed by VLBI proper motion studies, which generally show expansion, although not necessarily in a highly collimated way (e.g., Gwinn et al. 1992).

With the proliferation of molecular line observations at millimeter- and infrared-wavelengths, rotational lines from CO and vibrational-rotational emission from shock-excited H_2 became major tracers of outflowing gas. Indeed, wide-field H_2 surveys have become an effective tool for finding outflows (e.g. Stanke et al. 2000) in addition to high velocity CO and H_2O maser searches.

In particular, observations of the CO lines, which trace the bulk of the high velocity material, allow estimates of the physical properties of the outflowing gas. Churchwell (1999) compiles observational data and derived physical quantities for known massive bipolar outflows. In summary, he finds outflow masses, M_f, between a few and 5000 $M_\odot$, mass outflow rates, $\dot{M}_f$, ranging from 3×10^{-5} to 10^{-2} $M_\odot \mathrm{yr}^{-1}$, kinetic energies from 10^{46} to 6×10^{48} ergs, and outflow luminosities, L_f, between 0.2 and 1300 $L_\odot$. Thus, mean outflow masses and luminosities are 100 times greater than the values found in low mass SFRs. Notably, $\dot{M}_f$ increases monotonically with L_{bol} for L_{bol} ranging from 1 to $10^6 L_\odot$ (Shepherd & Churchwell 1996b). Churchwell (1999) finds $\dot{M}_f \propto L_{bol}^{0.7}$; see also Henning et al. (2000). This may provide important information on the outflow mechanism(s) and, as discussed by Norberg & Maeder (2000), on the star-forming process(es) itself.

3. Jets from Massive Protostars and Young Stellar Objects?

The interpretation of the H_2O proper motion data mentioned above calls for a jet to explain the maser acceleration (Mac Low et al. 1994). Direct evidence for this scenario is provided by the VLA detection by Reid et al. (1995, see also Wilner et al. 1999) of a non-thermal radio source with double jet morphology whose centroid is coincident with the center of expansion determined from VLBI proper motion measurements of the H_2O maser outflow in this region (Alcolea et al. 1993). The jet/H_2O source is coincident with a molecular hot core in the vicinity of the archetypical ultracompact HII region W3(OH). Using millimeter interferometry, Wyrowski et al. (1999) resolve this core in at least three hot (≈ 200 K) condensations, one of which is exactly centered on the non-thermal jet/H_2O source, for which a luminosity of a few times $10^4 L_\odot$ is derived, indicating that the embedded object is of intermediate, rather than high mass.

Sensitive radio continuum observations have the potential to reveal jets from and, even more fundamentally, the exact locations of embedded massive stars. The apparent paradox that the by far most luminous object in a given region may be difficult to locate is well illustrated by the example of Orion-KL. Here, VLA observations by Menten & Reid (1995) show that the weak thermal radio source I is coincident with the unique SiO maser source found in this region. Given that the SiO masers almost certainly require an exciting source with a luminosity in excess of $10^4 L_\odot$ strongly suggests that the radio source indeed is coincident with the massive protostar powering the region, which due to its extreme extinction is impossible to locate even at infrared wavelengths.

Another example for a radio source coincident with the center of activity is found in the Cepheus A region, where Garay et al. (1996) interpret the spatially elongated thermal emission from their source 2 as arising from a collimated jet of ionized gas (see also Hoare & Garrington 1995).

In summary, the evidence for collimated jets in high-mass SFRs is inconclusive at present. One lesson learned from the examples described above is that jet emission from protostellar objects, thermal or non-thermal, might in general be quite weak. With present technology, all of the radio sources discussed above would be impossible to detect in more distant regions like W49. Nevertheless, given the extreme extinctions in the regions in question, radio imaging with high resolution, high sensitivity, and high dynamic range may be the only way to find such jets.

References

Alcolea, J., Menten, K. M., Moran, J. M., Reid, M. J. 1993, in Astrophysical Masers, eds. A. W. Clegg & G. E. Nedoluha (Heidelberg: Springer), 225

Bachiller, R. 1996, ARA&A, 34, 111

Bonnell, I. A., Bate, M. R., Zinnecker, H. 1998, MNRAS, 298, 93

Churchwell, E. 1997, ApJ, 479, L59

Churchwell, E. 1999, in Unsolved Problems in Stellar Evolution, ed. M. Livio (Cambridge University Press), 41

Garay, G., Ramírez, S., Rodríguez, L. F., Curiel, S., Torrelles, J. M. 1996, ApJ, 459, 193

Gwinn, C. R., Moran, J. M., Reid, M. J. 1992, ApJ, 393, 149

Henning, T., Schreyer, K., Launhardt, R., Burkert, A. 2000, A&A, 353, 211

Hoare, M. G., Garrington, S. T. 1995, ApJ, 449, 874

Livio, M. 1999, Phys. Rep., 311, 225

Mac Low, M.-M., Elitzur, M., Stone, J. M., Königl, A. 1994, ApJ, 427, 914

Menten, K. M., Reid, M. J. 1995, ApJ, 445, L157

Norberg, P., Maeder, A. 2000, A&A, 359, 1025

Reid, M. J., Argon, A., Masson, C. R., Menten, K. M., Moran, J. M. 1995, ApJ, 443, 238

Shepherd, D. S., Churchwell, E. 1996a, ApJ, 457, 267

Shepherd, D. S., Churchwell, E. 1996b, ApJ, 472, 225

Stahler, S. W., Palla, F., Ho, P. T. P. 2000, in Protostars and Planets IV, eds. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 327

Stanke, T., McCaughrean, M. J., Zinnecker, H. 2000, A&A, 355, 639

Strelnitskii, V. S., Sunyaev, R. A. 1973, Soviet Astron., 16, 579

Wilner, D. J., Reid, M. J., Menten, K. M. 1999, ApJ, 513, 775

Wyrowski, F., Schilke, P., Walmsley, C. M., Menten, K. M. 1999, ApJ, 514, L43