JETS IN MOLECULAR CLOUDS +

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There is now growing evidence that the cosmic jet phenomenon manifests itself in a remarkable way in regions of active star formation embedded in dense molecular clouds. The first indications for oppositely directed, supersonic outflows from young stars were provided by molecular line observations (most notably of CO) which detected spatially separated regions of redshifted and blueshifted emission in association with embedded infrared sources. About twenty sources of this kind have been identified so far, and more are continuously being discovered; they typically have radii $\sim 10^{18}$ cm, velocities $\sim$10-50 km s^{-1}, dynamical ages $\sim 10^4$ yr, and energies $\sim 10^{46}$-10^{47} erg s^{-1} (see Bally and Lada 1983 for a review). Statistical arguments indicate that energetic outflows of this type are probably a common feature in stellar evolution, and that they occur in both massive and low-mass stars. Direct evidence that the outflows in many cases are highly collimated was subsequently provided by the detection of high-velocity Herbig-Haro objects (optical emission clumps with typical masses $\sim 10^{-5} M_{\odot}$) along the axes of the bipolar CO lobes. Proper-motion measurements are now available for a number of these objects (e.g., Herbig and Jones 1981), and they invariably reveal that the velocity vectors (of typical magnitudes 200-400 km s^{-1}) point away from the central star. The clumps are often found to consist of many sub-condensations which move independently with disparate speeds, but which nevertheless travel in the same general direction with an angular spread $\lesssim 10°$. Finally, radio continuum observations (e.g., Cohen et al. 1982) and deep CCD images (e.g., Mundt and Fried 1983) have shown that the collimation of the outflows is already well established on scales of $\lesssim 10^{15}$ cm.

The morphology of the bipolar emission sources detected in molecular clouds bears a striking resemblance to that of double radio lobes and jets observed on vastly larger scales in extragalactic sources. In both cases, collimated outflows are detected over several decades of scale on opposite sides of a compact source. In each case, the outflows terminate in extended emission regions which are formed when the jets ram against the ambient medium. And, in both cases, distinct emission knots are found along the jets which are most likely associated with shock waves.

+ Discussion on page 459

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The analogy with extragalactic sources has proven useful in formulating a unified interpretation of molecular-cloud outflows (Königl 1982). In turn, the study of these relatively nearby outflows may provide valuable information on the jet mechanism which is not available from observations of extragalactic objects. For example, the molecular sources are the first instance of jets where the motion of the head of the jet and the transverse expansion of the shocked jet material can actually be measured. The kinematic and spectroscopic data on Herbig-Haro objects likewise provide a unique input for general models of emission knots in jets (cf. Blandford and Königl 1979). In fact, recent detections of shocked optical line emission from nonthermal continuum knots in a number of radio jets (e.g., Brodie et al. 1983) support the hypothesis that the knots in stellar and in galactic jets have similar interpretations. Finally, the ability to measure the density and temperature structure of interstellar clouds by means of various atomic and molecular tracers again could prove useful for a general study of the interaction between jets and their environment.

Why do jets form in protostellar environments? One likely explanation is that they are produced by a combination of the same two ingredients that were originally invoked by Blandford and Rees (1974) to account for the production of extragalactic jets - namely, an isotropic stellar wind and a flattened mass distribution which confines it. Mass outflows are common in pre-main-sequence stars, and direct spectroscopic evidence for stellar winds has been reported already for several of the central stars in bipolar sources. Evidence is also rapidly accumulating from continuum infrared and from molecular line measurements for the presence of clumpy, high-density "tori" which could constrain the transverse expansion of the jets (e.g., Schwartz et al. 1983). One can argue on theoretical grounds (Königl 1982) that a stellar wind which propagates into an anisotropic density distribution could become unstable to the formation of transonic nozzles if the ambient density scaled with radius roughly as $\rho \propto r^{-2}$. Density distributions of this form are expected in isothermal clouds, and have in fact been inferred to exist in the vicinity of bipolar sources by molecular line observations as well as on statistical grounds (see Bally and Lada 1983). The anisotropy in the density distribution could have been induced by rotation, but an alternative interpretation is suggested by the correlation found in some of the sources between the bipolar axis and the direction of the ambient magnetic field as deduced from polarization measurements. In this picture, which could perhaps be relevant also in extragalacitc contexts, the density gradient is induced by magnetic stresses which inhibit cloud contraction normal to the field lines.

Radio continuum observations with $\lesssim 1''$ resolution are particularly valuable for the study of molecular-cloud jets. Such observations have already yielded detailed maps of jets on scales $\lesssim 10^{15}$ cm that are surprisingly similar (e.g., in revealing curvature effects) to VLBI maps of extragalacitc jets. A number of sources are unresolved on these scales, but their optically thick thermal spectra indicate that they may be produced in massive outflows which become neutral already on scales

$\sim 10^{14}$ cm (e.g., Simon et al. 1983). These observations may also help clarify a number of still outstanding problems, such as the discrepancy that often appears between the momentum discharge rate inferred from direct measurements of the central outflow and the substantially higher rate required to drive the expansion of the outer emission lobes.

REFERENCES

Bally, J., and Lada, C.J.: 1983, Astrophys. J. 265, pp. 824-847.
Blandford, R.D., and Königl, A.: 1979, Astrophys. Letters 20, pp. 15-21.
Blandford, R.D., and Rees, M.J.: 1974, Monthly Notices 169, pp. 395-415.
Brodie, J., Königl, A., and Bowyer, S.: 1983, Astrophys.J. 273 (October 1 issue).
Cohen, M., Bieging, J.H., and Schwartz, P.R.: 1982, Astrophys.J. 253, pp. 707-715.
Herbig, G.H., and Jones, B.F.: 1981, Astron. J. 86, pp. 1232-1244.
Königl, A.: 1982, Astrophys. J. 261, pp. 115-134.
Mundt, R., and Fried, J.W.: 1983, Astrophys. J., submitted
Shwartz, P.R., Waak, J.A., and Smith, H.A.: 1983, Astrophys. J. 267 pp. L109-L114.
Simon, M., et al.: 1983, Astrophys. J. 266, pp. 623-645.