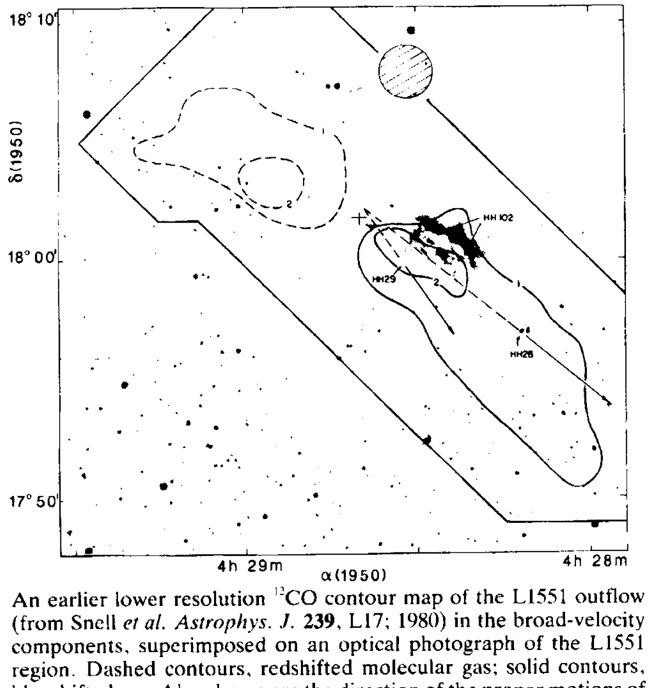
Astrophysics

Bipolar wind from young stars

from James P. Emerson

THE molecular cloud L1551 contains the best example of a collimated bipolar high-velocity molecular outflow driven by a young stellar object. Now high-resolution ^{12}CO observations have directly demonstrated the postulated windswept cavity and shell in this cloud (Snell, R.L. & Schloerb, F.P. *Astrophys. J.* **295**, 490; 1985). The complex observed morphology and kinematics can be neatly explained by the combination of two effects. First, a collimated high-velocity flow from the young stellar object IRS5 (infrared source 5) sweeps out a bipolar cavity in the molecular cloud, and compresses much of the material into a dense thin shell surrounding the cavity; and second, the cavity expands uniformly into the surrounding cloud. The biggest puzzle of all, however, still remains — what causes the collimated bipolar wind from the young star in the first place?

A key problem of astrophysics is the formation and early evolutionary stages of stars. Interpretation of the observations of young high-mass stars is particularly complicated because they are usually associated with clusters of other nearby stars, surrounding ionized hydrogen regions, ionization fronts and shocks. Therefore, many researchers hoped to get a clearer picture of star formation from studying low-mass stars forming in dark clouds, because these are relatively isolated objects and not expected to be associated with the complexities of ionized hydrogen regions.



An earlier lower resolution ^{12}CO contour map of the L1551 outflow (from Snell *et al. Astrophys. J.* **239**, L17; 1980) in the broad-velocity components, superimposed on an optical photograph of the L1551 region. Dashed contours, redshifted molecular gas; solid contours, blueshifted gas. Also shown are the direction of the proper motions of the two compact Herbig–Haro objects, HH28 and HH29; tracing their motion backwards suggests a common origin at IRS5 (cross). α, Right ascension; δ, declination.

Far from the anticipated simplicity, there has instead been mounting evidence that energetic jets and collimated outflows are commonly associated with young stars, even those of low mass. The energy input into the surrounding clouds from these bipolar winds could significantly affect the subsequent evolution of the cloud and its star-forming history. Some of these problems are analogous to those involved in understanding jets from galaxies, although jets from young stars are non-relativistic and do not involve such great energies (see Lada, C.J. *Ann. Rev. Astron. Astrophys.* **23**, 267; 1985).

When molecular-line observers first turned their telescopes towards the candidate young star IRS5, which is in the dark cloud L1551, they were surprised to find, in addition to the expected low-velocity molecular gas associated with the dark cloud, blueshifted and redshifted high-velocity gas located in oppositely directed bipolar lobes on the sky (see figure). The south-west lobe contains blueshifted gas and the north-east lobe redshifted gas. In the approaching lobe optical nebulosity can be seen because the flow is coming out of the dark cloud, but in the receding lobe no nebulosity can be seen because of the obscuring dust.

Although many examples of bipolar molecular outflows have now been found, L1551 remains prototypical as its proximity and orientation make it especially favourable for detailed observational study. Optical studies of the south-west lobe have identified shock-excited knots of gas (termed Herbig–Haro objects) whose proper motions are radially outwards from IRS5. Optical and high-resolution radio observations have both shown ionized jets emanating from IRS5 parallel with the much larger-scale bipolar outflow and orthogonal to a dense rotating torus of high-density material seen in CS (carbon monosulphide) observations and suggested by infrared polarization studies. Shock-excited molecular hydrogen is found at the edge of the flow, and some of the optical nebulosity is interpreted as reflected light from IRS5.

Snell and Schloerb have produced a complete ^{12}CO map of L1551 in the 2.6-mm line with the highest angular resolution (45″) yet used on this flow, together with lunar occultation measurements of 7″ resolution which clearly show the cavity and shell, and demonstrate that each lobe can be considered to be divided into two velocity components. The lower velocity component is in a thin shell at the periphery of the higher velocity component and contains a substantial fraction of the 0.9 solar masses of material in the outflow. The data and the overall flow shape can be neatly and consistently interpreted in terms of the collimated bipolar wind from IRS5 driving gas radially outwards at about 12 km s^{-1}, while the bubble thus created expands uniformly at a velocity of about 4 km s^{-1}. The mass now contained in the cavity and its surrounding compressed shell is close to that expected to be swept up if the cavity volume originally contained molecular gas at the ambient density of the undisturbed central parts of the cloud.

As Snell and Schloerb point out, although the mechanical luminosity of the wind is only a small fraction of the luminosity of the embedded star, the mechanism by which the energy of IRS5 is converted into momentum in the flow is as unknown in L1551 as it is in the other examples of this phenomenon.

It is widely believed that many young stellar objects, still evolving towards the main sequence, are surrounded by remnants of their parent cloud in the form of a rotating circumstellar torus or disk. It is crucial for theories of the formation of planetary systems and stars that the disks and their interaction with the stars and their immediate environment be understood. These disks are commonly assumed to be involved in the production of jets and bipolar outflows by an interaction between the young star and the surrounding torus or disk of material. It is thought that the interaction producing the jets is mediated by some combination of local density structure, magnetic fields, rotation and accretion of material, but theoretical models have failed to provide any widely accepted explanation.

Many of the current observations make use of techniques such as interferometry and polarimetry in the infrared and millimetre spectral regions in attempts to identify clearly these disks and to define their properties and how they relate to the jets (for example, Beckwith, S. *et al. Astrophys. J.* **287**, 793; 1984 for HL Tau, which also lies in L1551), but it seems more probable that a new theoretical model is required to explain how the collimated jets from young stars are driven. □

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