STAR FORMATION

When protostars cease trading

A. P. Whitworth

THE final stages of star formation are accompanied by violent dynamical instabilities, as the star seeks simultaneously to accrete more material and to shed excess angular momentum. It is only when this trade in mass and angular momentum has virtually ceased that the star can be observed in its own right. By this stage the star has either accreted or blown away most of the gas and dust surrounding it. Elsewhere in this issue (*Nature* **342**, 161–163; 1989) Y. Fukui and co-workers report their analysis of millimetre-wave observations of powerful molecular outflows associated with young stars from which they derive important new constraints on the duration of the early accretion phase.

Stars form from dense clumps of interstellar gas which are pulled together by self-gravity. The central regions of the clump, being the most dense, condense out as a star on a rather short timescale. Normally, the outer material has too much angular momentum to fall directly onto the star, and so in the first instance it is deposited onto a rotating circumstellar disk. Such disks are commonly observed around young stellar objects, both in continuum emission from dust and in line emission from molecules.

Material in the disk is subject to magnetic stresses which remove angular momentum, so enabling the material to spiral inwards towards the central star. Given sufficient time this material is accreted onto the stellar equator. Much of the gravitational energy and angular momentum released by the inward-spiralling material in the disk is transported away by an outflow of matter and hydromagnetic waves channelled along the poles of the star's rotation axis, at right angles to the disk.

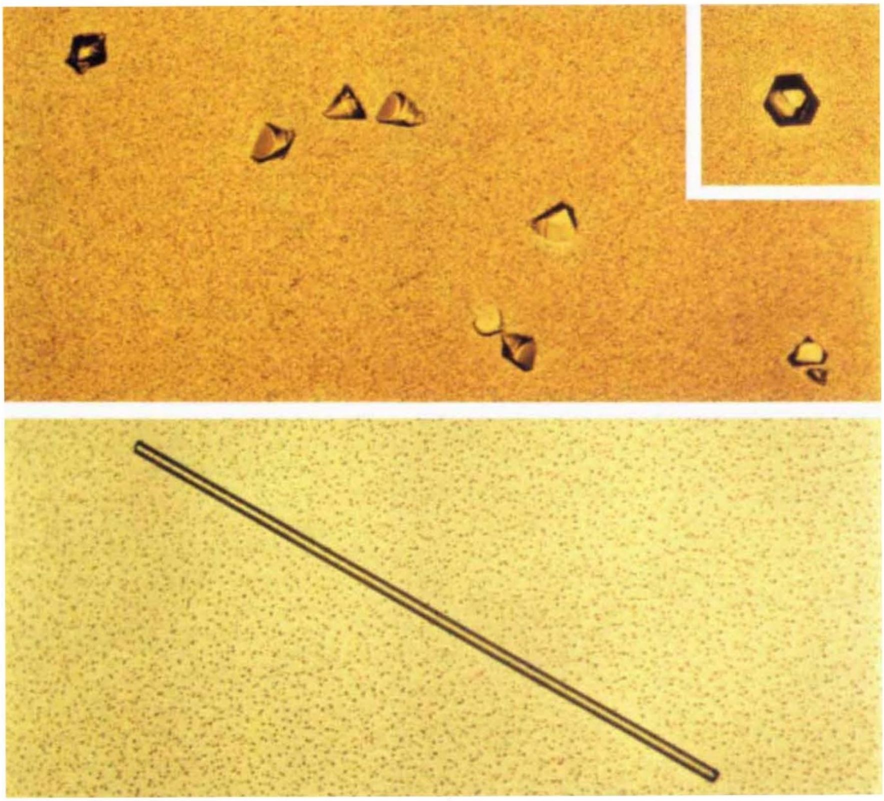
Near the star this outflow often takes the form of a jet. Where this jet interacts with the ambient interstellar medium, it may excite a string of Herbig–Haro objects (small clumps of emission nebulosity whose optical-line spectrum indicates that they have been heated by a shock). Sometimes the string terminates in a bow shock which can be mapped in the infrared line radiation of molecular hydrogen. Further out still, carbon monoxide emission at millimetre wavelengths reveals extended lobes of molecular gas receding from the star at supersonic speeds.

Ultimately the supply of accretable matter runs out, the accretion flow subsides, and the associated release of energy and angular momentum driving the outflow declines; the jet ceases to blow; the Herbig–Haro objects cool off; and the molecular lobes merge with the ambient interstellar medium. Parts of the residual disk may coagulate to form planets and the remainder is dispersed.

The problem is to piece together a detailed evolutionary sequence for young stellar objects, so that the different stages in the process outlined above can be distinguished observationally. The observed diversity of young stellar objects associated with disks and outflows represents a range of initial protostellar clump masses, with a range of initial angular momenta, observed at different stages in their evolution, and from different viewing angles (relative to the rotation axis). The observational data set is distorted by selection effects. The work by Fukui *et al.* is an important step towards solving this problem.

Previous investigations of outflowing

Diversity of laser snowflake crystal forms



LASER SNOW is the name given to powdery clouds first observed by A. Tam, G. Moe and W. Happer in a caesium vapour exposed to laser light (*Phys. Rev. Lett.* 35, 1630–1633; 1975). It seems that the grains consist of caesium hydride, made when caesium atoms excited by the laser radiation react with hydrogen in the ambient vapour. The particle growth is a nucleation process similar to that responsible for raindrops, which is why T. Tanaka and colleagues at Kyoto University recently joined with K. Sugiyama of the Japanese National Meteorology Research Laboratory to study their morphology (*Phys. Rev. Lett.* 63, 1390–1392; 1989). To their surprise, the crystal shapes depend exquisitely on the conditions in the vapour cell: whiskers up to 400 μm long (bottom) are produced when the temperature of the caesium–hydrogen vapour is 300 °C and the laser power is relatively low (80 milliwatts); with the same laser power, but at 250 °C, small polyhedra, typically having a hexagonal cross-section, are produced (top, inset); reducing the temperature further (to 230 °C) while raising the laser power to 300 milliwatts results in pyramidal crystallites (top, main picture). Not only does the laser promote the caesium–hydrogen reaction, but also by virtue of the photoelectric effect, it positively charges the particles. The authors argue that electrostatic repulsion prevents the crystals from growing by the coalescence of smaller particles. Instead, they argue, individual CsH molecules condense onto the grains, a process enhanced by the 'electron harpoon' mechanism. Caesium hydride molecules are moderately electronegative and so easily capture the crystal's photoelectrons. The resultant electrostatic pull quickly attaches new molecules onto the crystal surface. ☐