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The Secret Inner Life of the Orion Nebula

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Abstract: Beneath the familiar surface of the Orion Nebula is a spectacular molecular hydrogen outflow from a young stellar object, of very unusual morphology. In this paper I briefly discuss this outflow, its possible origins, and its interaction with the Nebula.

Keywords: ISM: jets and outflows — ISM: individual (OMC-1) — stars: formation — stars: pre-main sequence — stars: winds, outflows — H II regions

1 Introduction

The familiar Orion Nebula is actually a cavity on the surface of a molecular cloud, within which lies a large star-formation region. In addition to the cluster(s) of young stars, the cloud also contains the by-products of star formation: stellar outflows—in particular, a striking molecular hydrogen outflow. This nebula, known for over a decade, has recently been seen to be composed of an array of scores of 'fingers': linear streamers of molecular hydrogen gas, often with intricate internal structure. These are believed to be formed by knots of gas—ejected from a young stellar object embedded in the cloud—that impact the ambient medium, setting up bow shocks. Although such objects are often seen in regions of star formation, this extensive array of them forms an object that is, as far as we know, unique in the heavens.

2 Large-scale Structure of Orion

The Orion star-formation region is the closest region of massive star formation. As such, it affords us a unique opportunity of studying the formation of high-mass stars. (Here, high-mass stars are those with masses greater than one solar mass). The Orion complex lies 160 pc below the Galactic plane, and 450 pc from Earth. The star-forming region consists chiefly of Orion A and B, molecular clouds named for their most prominent H II regions. Each of the two clouds contains about $10^5\,M_\odot$ of material (Genzel & Stutzki 1989). Orion B (covering about $1200\,\mathrm{pc}^2$) is associated with the Horsehead Nebula and NGC 2023, 2024, 2064, 2068 and 2071. Orion A, southwest of this, covers about $1800\,\mathrm{pc}^2$ and is associated with the Orion Nebula (aka NGC 1976, M42). The oldest of the stars in the Orion A and B clouds are younger than 12 Myr (Brown, de Geus & de Zeeuw 1994).

3 The Orion Nebula

The Orion Nebula is a blister-type H II region, a cavity formed in the surface of the molecular cloud by ultraviolet radiation from the Trapezium stars (especially θ^1 C)—stars <1 Myr old—which lie about 0·2–0·3 pc in front of the nebula (Baldwin et al. 1991). The H II region as a whole has a radius of 0·3–0·5 pc (Hillenbrand 1997). Behind the H II region is an ionisation front and photodissociation region which is the interface between the H II region and the molecular cloud; this has a thickness of about 10^{-4} pc (O'Dell 1993). The far edge of the molecular cloud itself is about 500 pc away (Brown et al. 1994), and so is perhaps as much as 50 pc thick in the vicinity of the Orion Nebula. Figure 1 shows a diagram displaying the relationship between the various layers of the nebula and molecular cloud.

The optically visible nebula emits lines typical of H II regions, such as [NII], [OIII] and [SII], and hydrogen recombination lines. These various layers are partially revealed in the Orion Bar, a bright linear structure about 2 arcmin southeast of the Trapezium. The Bar is formed by the curvature of the H II region; at this point the cavity curves steeply towards Earth, allowing us to see the PDR edge-on (Hogerheijde, Jansen & van Dishoeck 1995).

The surface of the nebula is not smooth, but composed of a variety of wisps, bubbles and ridges, whose brightness and spectra are dependent mainly on their distance from the Trapezium (Wen & O'Dell 1995). The nebula is also the site of at least two systems of Herbig–Haro (HH) objects. HH objects are by-products of star formation: emission nebulae formed when an outflow from a young star impacts surrounding material, shocking both outflowing and ambient material. The southern system (HH 202–204) probably has its source(s) in the vicinity of the Trapezium, while the northern system includes the fast, optically-emitting 'fingers' detailed below (O'Dell 1997).

4 Beneath the Nebula

At 2 μm, the brightest object in the region is the Becklin–Neugebauer object (BN), thought to be about 0·5 pc beneath the surface of the Orion Nebula. BN is accompanied by the infrared Kleinmann–Low (KL) nebula, as well as the molecular hydrogen outflow. The entire infrared nebula is often referred to as BN-KL. Although BN dominates the 2 μm image, it is not the most luminous object in the cluster. The most luminous object is IRc2,

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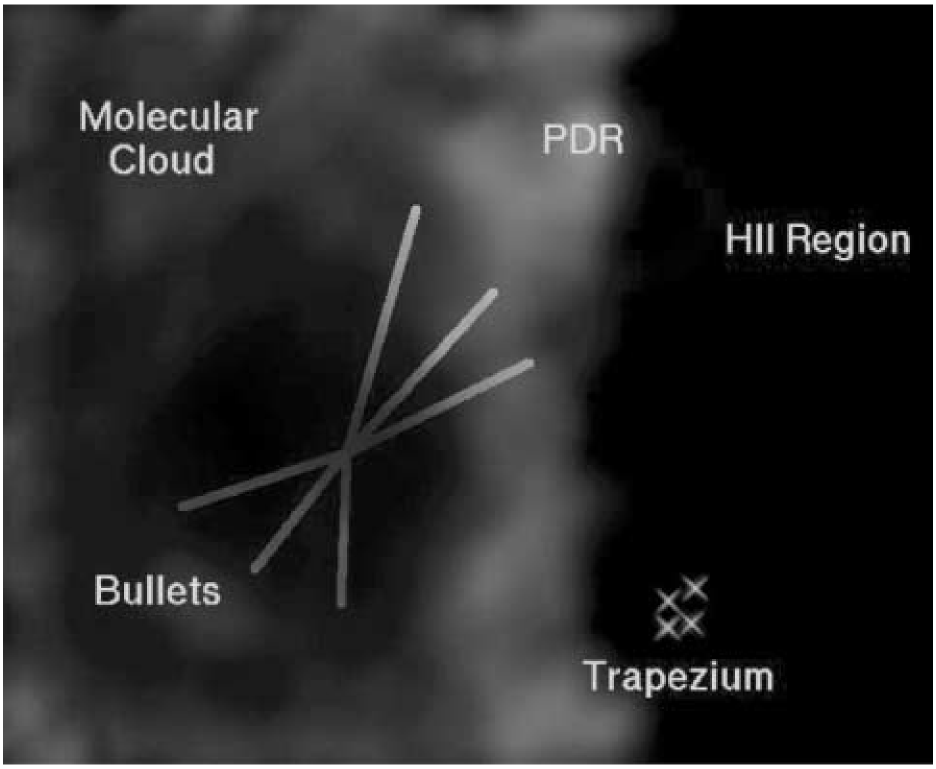

Figure 1 A diagram showing the molecular cloud/H II region interface, and possible location of the outflow. Observer is to the right.

about 9 arcsec to the southeast of BN, with a total luminosity of 2–10 × $10^4\,L_\odot$ (Genzel & Stutzki 1989). This deeply-embedded object has long been considered a likely candidate to be the exciting source for the outflow, because of both its luminosity and its central location within the outflow. However, Dougados et al. (1993) have found that at 3·8 μm IRc2 is resolved into four objects [although the polarisation data of Menten & Reid (1995) suggest that not all of these objects are self-luminous]. In addition, Gezari, Backman & Werner (1998) find that the total luminosity of IRc2 is only $10^3\,L_\odot$. The identification of IRc2 as the source of the BN-KL outflow therefore remains tentative.

Beckwith et al. (1978), using a single-beam spectrometer, found H_2 emission in a large, two-lobed structure in the BN-KL region. In 1984, Taylor et al. found that the H_2 actually took the form of linear structures; in the same year, Axon & Taylor (1984) discovered optical bow shocks (recognized as HH objects) up to 2 arcmin north of the Trapezium. Allen & Burton (1993) confirmed that the H_2 structures (now known as 'fingers') and optical HH objects were related. Their images showed that the fingers were capped by bow shocks prominent in [FeII] 1·64 μm emission. [FeII] is produced by shocks similar to those that emit [SII] and [OI]; in other words, the caps are the optical objects found by Axon & Taylor (1984). In most of these objects, the H_2 emission is quite separate from the [FeII], indicating that the shocks are fast enough to dissociate H_2 at their heads. The correspondence of optical and [FeII] emission confirms that these are fast shocks. The presence of the optical emission also implies that these objects are moving into a region of lower extinction, i.e., out of the molecular cloud and into the PDR.

The outflow contains over 50 of these molecular hydrogen fingers—although counting them is difficult because they do not all have a linear morphology, and they often overlap—extending up to 2 arcmin from BN/IRc2. The total mass of the bullets is $\sim 10^{-1}\,M_\odot$, and the energy in the outflow is $\sim 5 \times 10^{46}$ erg (5×10^{39} J). The dynamical lifetime of the northernmost fingers, i.e. the time necessary for them to reach their current locations, is less than 1000 yr (Allen & Burton 1993; Burton & Stone 2001). The proper motion studies of Lee & Burton (2000) show that these northern fingers are moving at velocities of roughly 200 km s^{-1}.

Although these northern molecular hydrogen fingers were found by ground-based observations, the inner regions of the outflow, within about 50 arcsec of BN, still appeared as a smooth fan-shaped region. Recent HST images (Stolovy et al. 1998; Schultz et al. 1999) have shown that this region, too, is composed of linear, finger-like structures.

Figure 2 contains the well-known optical HST WFPC2 image of the centre of the Orion Nebula (O'Dell & Wong 1996); the box delineates the area shown in Figure 3. Figure 3a shows an HST NICMOS image of this region in the light of Pa α at 1·87 μm, which comes from the photo-excited gas at the surface of the nebula, and is very similar in appearance to the Hα emission shown in Figure 2. Figure 3b shows the same field in H_2 emission from the BN-KL outflow, clearly showing the linear finger

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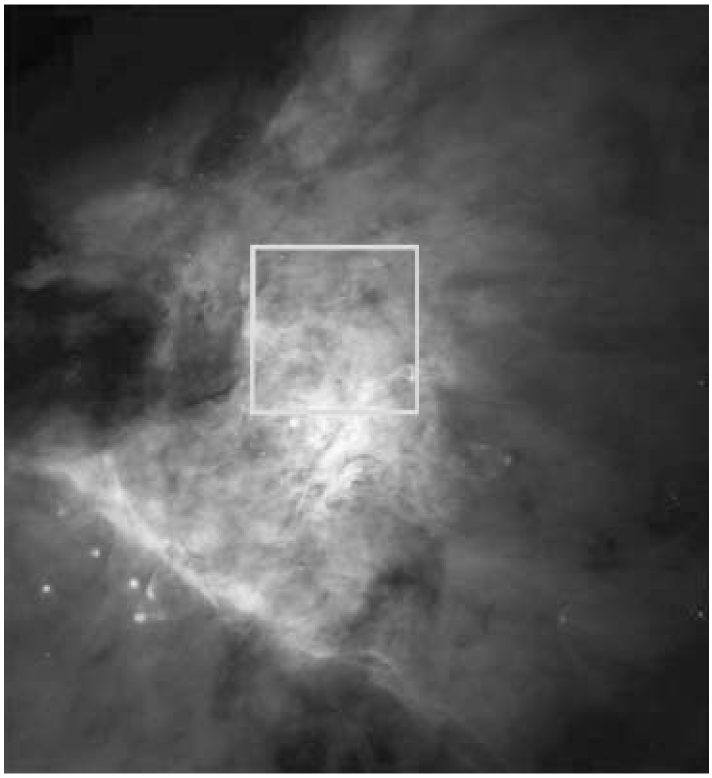

Figure 2 HST WFPC2 image of the Orion Nebula. Red is [NII], Hα is green, [OIII] is blue. The box defines the region seen in Figure 3, and is about 90 arcsec on a side. (Image courtesy C. R. O'Dell.)

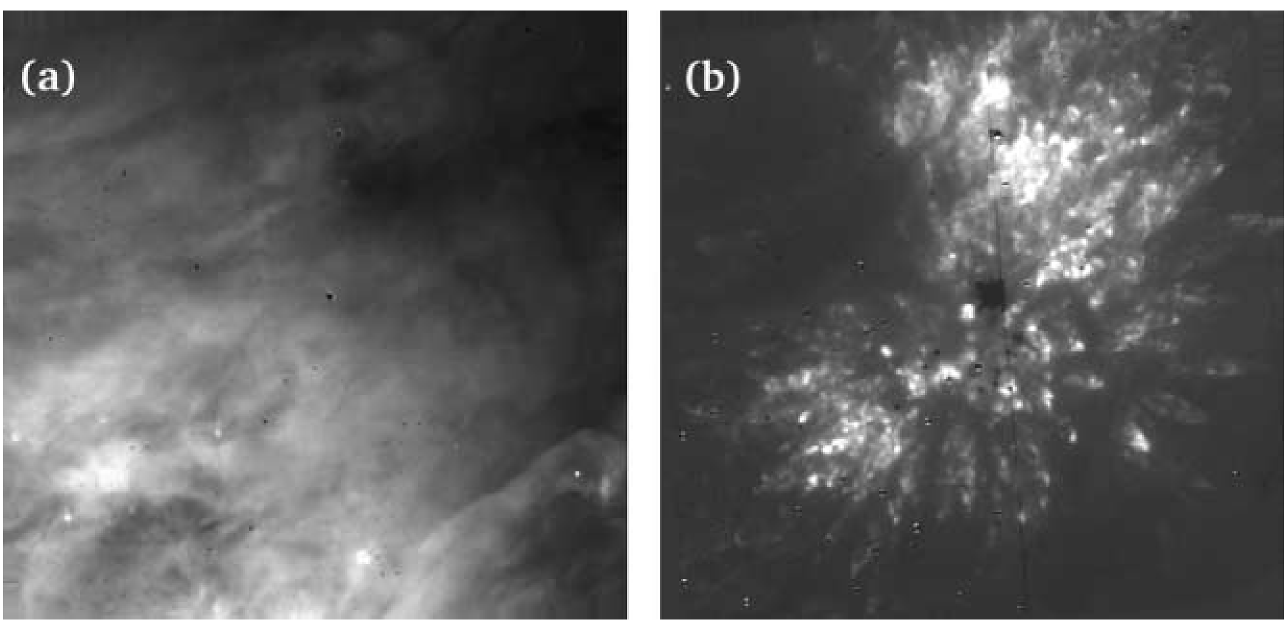

Figure 3 HST NICMOS images of the BN-KL region. (a) 1·87 μm Pa α emission from the surface of the nebula. (b) 2·12 μm H_2 emission from the YSO outflow embedded within the molecular cloud beneath the nebula. The two fields are identical. They are about 90 arcsec on a side, centred on BN.

structures. (Both of these figures have been continuum-subtracted, and dark spots show regions where stars have been removed.) This image only covers the central 90 arcsec of the outflow; the northern fingers described above are off the field. The difference in morphology between these two wavelengths is not due to differential extinction between 1·87 and 2·12 μm, but instead reveals the difference between the emission from the surface of the nebula,

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and the YSO outflow embedded in the molecular cloud beneath it.

In addition to the northern fingers (201, 205–207, 210), there are also a number of other objects in the region which exhibit optical and [FeII] emission. (HH 208 is one of these; most of the others are as yet unnamed.) This emission generally is highly blueshifted (O'Dell et al. 1997), indicating that they are Herbig–Haro objects rather than part of the nebular emission. A number of these are also associated with H_2 emission (see Figure 1 of Schultz et al. 1999). The fact that they are associated with optical emission implies that they are moving out of the molecular cloud and into the PDR, much like the northern fingers. Figure 1 shows a possible outflow orientation, in which some fingers are beginning to emerge from the cloud into the PDR.

5 Production of the Fingers

Any of the fingers standing alone would be fairly unremarkable. Young stars frequently possess outflows which, upon encountering ambient material, result in shocks set up in both the ambient and outflow material. If the outflowing material takes the form of fast-moving knots, or of a jet, the resultant shocks can take the form seen in the fingers in Orion. (Few of these, however, display the intricate structure seen in the inner fingers, which may be intrinsic to the finger, or may be the result of a superposition of individual fingers in our line of sight.)

What makes this nebula a remarkable object is the large finger array. The first explanation that may come to mind is that it is produced by a series of jets, or a precessing jet. A precessing jet would have to be intermittent, and of short duration, to produce the distinct individual fingers seen. While a single object may have two oppositely-directed jets, scores of jets would be needed to produce the array, and it is difficult to imagine a mechanism by which so many individual YSOs might produce jets with similar velocities, aligned in such a way, within a relatively short period of time.

Current theories posit a simultaneous, common source for the fingers. Perhaps the most intuitive explanation is that the fingers are the result of a large number of clumps accelerated by some explosive event within the cloud. However, theoretical studies of clump acceleration (e.g. Stone & Norman 1992; Xu & Stone 1995) have found that clumps are fragmented, rather than accelerated, producing a very different morphology. Another model is that of Stone, Xu & Mundy (1995); in this scenario the knots are formed and accelerated *in situ* through Rayleigh–Taylor instabilities. These result from the mixing of winds of different densities, such as the collision of an outflow with a previous, less dense outflow. The two separate winds might be the result of successive outflows from a single source, or possibly the second outflow could result from a separate, but nearby source. For a more detailed examination of this model and its relevance to Orion KL, see Burton & Stone 2001.

6 Disruption of the Cloud

Figure 4 shows the HST NICMOS field in 2·15 μm continuum, with a few interesting continuum features marked. The previously known infrared sources IRc3 and IRc4 are seen to be arcs with long diffuse 'tails' [this was first noted in the work of Stolovy et al. (1998)]; these tails have molecular hydrogen bullets emerging from them. One interpretation of the origin of the tail structures is that they are tunnels created in the cloud by the passage of the bullets; these tunnels are then lit from within by the infrared source(s) embedded in the cloud.

The region marked 'Dark Cloud' in Figure 4 may be a foreground remnant of denser cloud material, now being disrupted by the outflow. This structure can also be seen in Figure 3b, apparently obscuring some of the fingers in the southwestern part of the outflow. To the west of it lies a further faint area of emission which exhibits significant linear and circular K-band polarisation (Geng 1993; Chrysostomou et al. 2000—the IRc3 tail also exhibits high polarisation). This implies that these regions are being illuminated by the infrared sources within the cloud, possibly through openings created by the passage of the bullets.

North of BN, we find two other structures. The 'Crescent' appears to be a dense knot of cloud, illuminated from below by BN. Its appearance is reminiscent of the 'pillars' of the Eagle Nebula (Hester et al. 1996). The 'V' is another continuum structure with some H_2 emission. This emission, like that in the Crescent, is almost certainly shock-excited. The coincidence of strong continuum and H_2 emission would suggest a fluorescent mechanism for the excitation of the H_2, but there is no evidence of a source of sufficient FUV photons in this region. Emerging from the northern end of the 'V' is a linear H_2 feature which

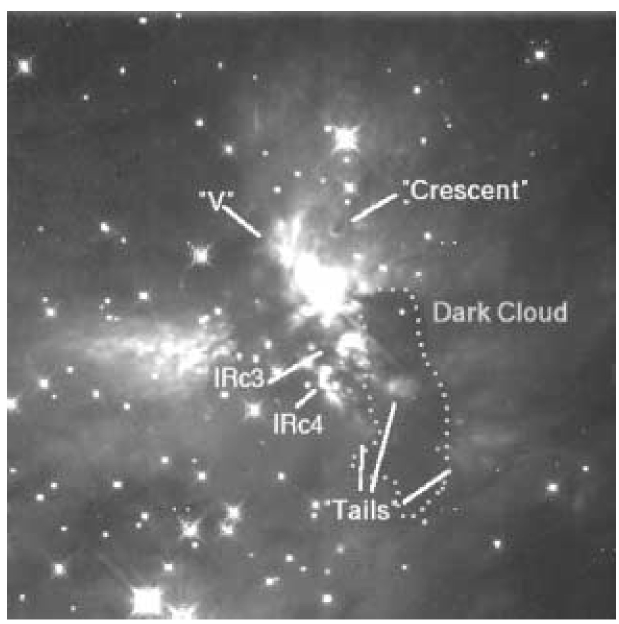

Figure 4 HST NICMOS 2·15 μm continuum image of the BN-KL region. This is the same field as in Figure 3. See the text for an explanation of the labels.

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Schild, Miller & Tennyson (1997) speculate is a jet terminating in a ring. However, the UKIRT Fabry-Perot data do not show an especially high velocity for this region (Schultz & Burton 2001). Schultz et al. (1999) speculate that the 'V' and 'jet' are the result of the confinement of the flow by the molecular cloud. (Note the absence of emission in the northeast quadrant of Figure 3b.)

7 Current Work

Some of the mysteries to be solved here are: What is the source of the outflow? How were the fingers produced? How has the outflow changed the environment of the molecular cloud, thereby affecting future (or current) star formation? Is an outflow of this type actually unusual, or just a brief stage in the life of a high-mass YSO?

Current research on the fingers is focusing on the velocity of the knots. Figure 5 shows the southern two-thirds of the NICMOS field (the entire field is shown in Figure 3b). Selected knots are shown with velocity profiles taken from UKIRT Fabry-Perot data (see Chrysostomou et al. 1997). The velocity profiles of a large number of morphologically interesting structures (e.g. bow shocks of various shapes, knots associated with known HH objects, etc.) in the NICMOS image were examined. It was found that only a handful of profile shapes were represented in the field, and that very few of these profiles had red components (Schultz & Burton 2001). This result has implications for the orientation of the outflow: if any of the outflow extends back into the molecular cloud, extinction is preventing us from seeing it.

We are also comparing the shapes of the line profiles to shock models in which parameters such as shock speed, bow shape and viewing angle vary. The determination of these parameters for individual knots or fingers will allow us to constrain the velocity and orientation of the outflow. Proper motion studies are also necessary for this, as well as being an important key to determining the source of the fingers.

Other ongoing research deals with the spectra of the fingers. The relative strengths of the lines (both molecular hydrogen and atomic lines) are dependent on parameters such as shock speed and gas density. Along with the space velocity information from the studies mentioned above, these observations provide insights into the expansion of the outflow, including the amount of energy and momentum it deposits into the molecular cloud.

8 Summary

The Orion Nebula is a cavity in the side of a molecular cloud, excavated by UV radiation from the Trapezium stars. Within the molecular cloud are a number of young stellar objects, one of which is responsible for a large molecular hydrogen outflow. This outflow is unusual in that it has taken the form of an array of linear structures, termed 'fingers', radiating from a point a few arcseconds south of BN. The fingers themselves are not difficult to explain; structures of this type are often seen in outflows from YSOs. The unusual aspect is the fact that there are over 50 fingers, in a fan-shaped outflow, extending over more than 2 arcmin (0·3 pc).

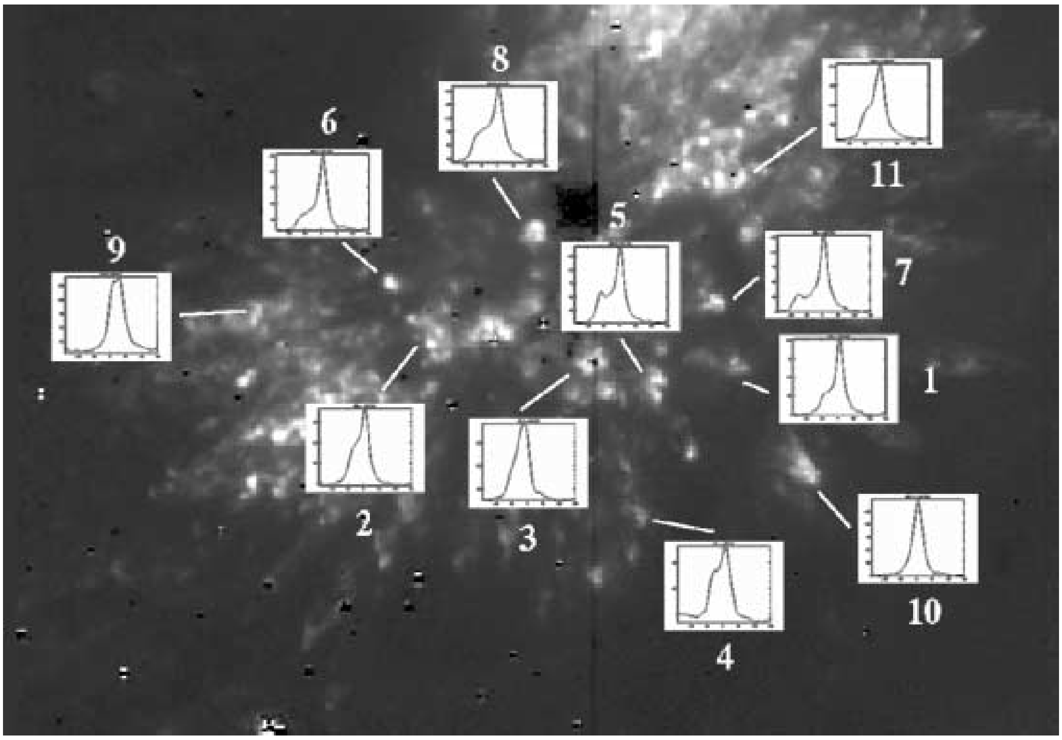

Figure 5 Grayscale: the bottom two-thirds of Figure 3b. The plots are velocity profiles taken from UKIRT Fabry-Perot data. Each plot is given a number, which is the number of the object in Chrysostomou et al. (1997). The y-axes of the plots are arbitrary; the x-axes all range from $-140\,\mathrm{km\,s^{-1}}$ to $+150\,\mathrm{km\,s^{-1}}$. The plots show that all of the knots are blue-shifted.

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The deeply-embedded young stellar object IRc2 is generally considered to be the most likely candidate for the source of this outflow, but the identity of the latter is still undetermined. Also undetermined is the mechanism by which this array of objects was produced; one plausible model involves two winds of different densities colliding to produce Rayleigh–Taylor instabilities. These in turn form knots *in situ*, already accelerating, within the flow, which become the tips of the fingers. The uniqueness of this object is also due to its (probably) short lifetime; with dynamical timescales of order 1000 yr, and cooling times for the shocks of $\sim$1 yr, this is likely to be a very brief stage in the life of a high-mass YSO. Even if it is a common stage, its short duration means that we are fortunate to be able to observe it.

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