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Gas Jets Associated with Star Formation

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One of the most remarkable and unexpected discoveries in astronomy in the past two decades is that very young stars emit energetic jets of material into their surroundings. The large-scale motions corresponding to the relatively gentle collapse of gas and dust to form a star do not predominate in the dark clouds within which stars form. Rather, the more obvious ordered motions are either rotation or those of energetic outflows of material from protostellar objects.

Summary. Young stellar objects of both high and low luminosity emit energetic jets or winds of material that are often highly collimated and often bipolar. Near the stars, turbulent swept-up gas is observed in the emission of interstellar molecules such as carbon monoxide, and small, bright regions of water maser emission and the nebulous bright patches known as Herbig-Haro objects appear to be participating in the outflows. There are striking changes in chemical abundances associated with the attendant shocks. Probably every star goes through this phase, which may mark the end of its period of accretion.

Much of what has been learned about this phenomenon has come from observations of the radio-wavelength emissions from interstellar molecules. Hints of this situation were already apparent in the first detections of polyatomic molecules in interstellar space in the late 1960's (*1*). The initial observations of OH· and H_2O emission at centimeter wavelengths showed evidence of material in interstellar clouds moving at velocities along the line of sight in excess of 100 km/sec.

Outflows of material, frequently bipolar in appearance, are evident in the surroundings of both the very luminous, highly obscured protostellar condensations and the less luminous young stars of lower mass that are visible near the surfaces of the interstellar clouds. Two phenomena clearly related to the outflows are the intense maser emissions of water vapor in small knots (*2*) and the Herbig-Haro objects, which are bright, visible patches of nebulosity (*3*); both show motions away from associated protostars. These processes are energetic and not easily explained.

The Outflows

The molecule chosen for the first studies of the physical properties of interstellar clouds was CO, because it is both abundant and easily excited by collisions with neutral or molecular hydrogen (the dominant species). The first suggestion of the outflows came from observations toward the Orion region (*4*) showing faint, broad wings on the otherwise narrow CO emission profile that correspond to high-velocity gas motions along the line of sight. Maps made with the spatial resolution of available radio telescopes (1 to 2 arc minutes) were unable to isolate this high-velocity motion. Subsequently, weak, broad-line wings were found toward several other regions, and eventually one source was found with enough extent that it could be mapped in detail (*5*). An optical photograph of this region, Lynds 1551 (L1551), with the CO map superimposed is shown in Fig. 1. The two CO lobes to the southwest and northeast are jets of somewhat collimated gas that seem to have been blown out of the infrared star in the center of Fig. 1. Many more such jets have been found (*6*). The degree of collimation (the opening angle) varies considerably. Some of the higher resolution maps show thinner lobes whose extents are a few light years in some cases. When a search is made, a candidate for the central source, the driving engine, is usually found.

The energy content of the CO lobes is large. Most of the mass of gas in dark clouds is in the form of molecular hydrogen, and it is possible to infer the amount of that gas from the measured amount of CO. The masses in the CO lobes range from 0.1 to 100 times that of our sun, and the velocity of dispersion in the lobes ranges from a few up to 100 km/sec. Combining the estimates of mass in the outflows with the measured velocities, we find kinetic energies in the range of 10^{44} to 10^{47} ergs for the CO lobes (the sun radiates about 10^{41} ergs in 1 year). From the differences in velocity between the lobes and their size, characteristic lifetimes between 10^3 and 10^5 years can be determined for the flows. From these energies and time scales, we infer energy rates or mechanical luminosities that are as much as 3000 times the rate of energy output of the sun.

A striking feature of many of the outflows is the intense emission in the 2-μm wavelength vibration-rotation transitions of molecular hydrogen near the outer edges of the outflows (*7*). Strong shocks, presumably the result of the collision of

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the massive, rapidly outward-moving gas with the stationary medium, are required to produce this radiation. The strength of this shock-induced radiation implies an energy flow into the shock that is typically 10 percent of that inferred for the CO flow.

One important property of the outflows is that, except for the large difference in velocity between the positive and negative CO lobes, there is little systematic variation of velocity across each lobe. That is, at each point along a lobe there is essentially the same broad emission line (*8*). If a steady, slow wind were plowing into a tenuous gas, a gradual deceleration would be expected, with the most distant material moving at the lowest speed. However, an explosive wind moving into a tenuous gas might show its highest velocity components at the greatest distances. The actual situation appears to be gas swept up into a shell by a supersonic wind. The great width of CO emission lines observed at all positions probably results from instabilities that occur when the supersonic wind pushes on the shell. The CO maps of jets show only the swept-up gas; the actual material of the wind does not appear in those maps, presumably because it is fast and of low density or perhaps because it is composed of neutral atomic material rather than molecules and grains of dust.

In addition to detailed studies of individual outflow sources, there have been surveys of large numbers of dark clouds to deduce the frequency of occurrence of the outflow phenomenon (*9*). Enough flows were found to suggest that the frequency of occurrence is comparable to the rate of formation of stars similar to our sun. This argues that every star, or at least every star as massive as our sun, goes through this outflow phase before it settles into its lifetime of hydrogen burning on the main sequence. If that is so, the formation of jets is an inevitable part of early stellar evolution. In addition, the flows may have a profound effect on the chemical state and physical properties of the clouds (*9, 10*).

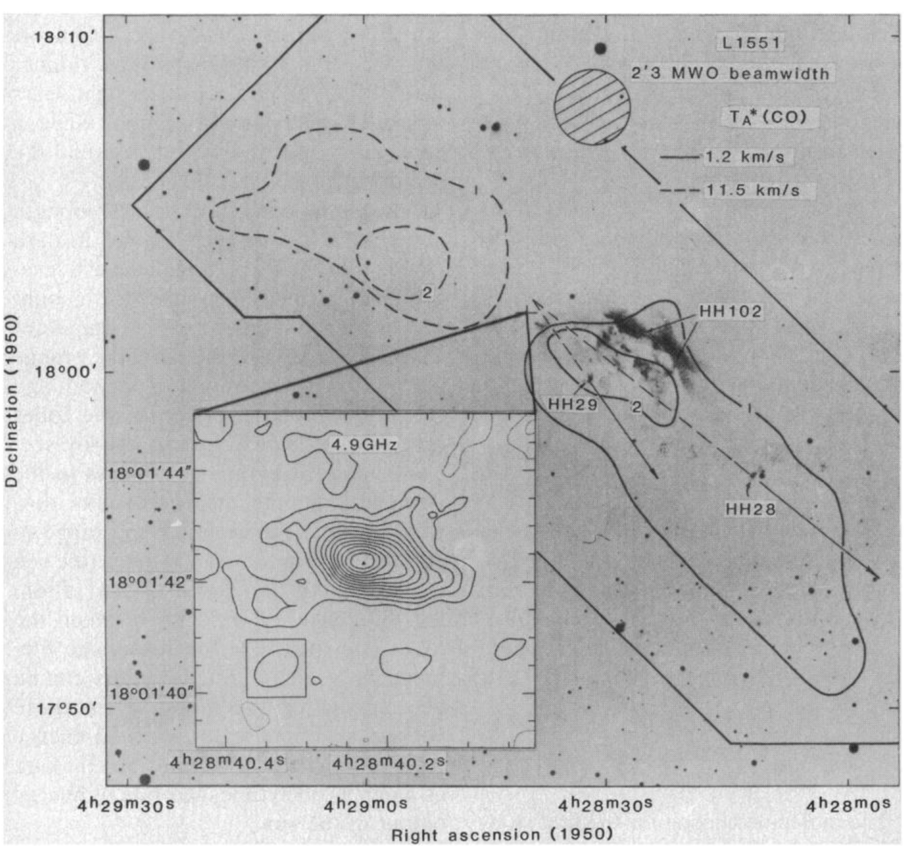

Fig. 1. Contour map of the $J = 1$ to 0 antenna temperatures of CO in the broad-velocity components, superposed on an optical photograph of the region taken with the 4-m telescope at Kitt Peak National Observatory. The map was made with the 5-m radio telescope of the Millimeter Wave Observatory (MWO) of the University of Texas at 2.3–arc minutes angular resolution. Blue-shifted gas is to the right, red-shifted to the left. The central star, IRS-5, is shown by the cross. The directions of the motions of Herbig-Haro objects HH28 and HH29 are shown, suggesting a common origin at IRS-5. T_A* designates the brightness temperature of the map. Optical photograph by S. E. Strom. (Inset) A high-resolution continuum map of IRS-5 taken with the Very Large Array, showing alignment of the small-scale jet with the large-scale flow. [From (*5, 47*), courtesy of *Astrophysical Journal*]

Water Masers

Radiation from interstellar water vapor is observed primarily as an intense emission from natural maser action at a wavelength of 1.3 cm (*1*). The radiation emanates from small regions either in the atmospheres of evolved stars or in the surroundings of newly forming stars. Near the new stars it appears as tiny, bright spots of emission 10^{12} to 10^{14} cm in size and scattered over regions 10^{16} to 10^{17} cm in extent, usually with Doppler-shifted velocities of a few to several hundred kilometers per second with respect to the surroundings. The number of spots and their brightnesses are generally greater if the nearby stars are more luminous (*11*). With very long baseline interferometry (VLBI), it is possible to measure transverse motions of these spots with respect to one another, with velocities comparable to the radial velocities implied by their Doppler shifts. In the Kleinmann-Low (KL) infrared nebula in Orion, the nearest location of high luminosity star formation, a VLBI study of the motions of the H_2O masers showed that they all appear to be moving away from a young stellar object known as IRc2 (*12*). This study was really the first to show unequivocal evidence of the outflow of dense material from regions of star formation. The pattern of motions in the Orion region requires acceleration of these objects over an interval of about 1000 years; a single explosive event seems unlikely.

Precise estimates of the masses of these objects are difficult to make because of the basic nonlinearity of the maser process. However, the densities must be of the order of 10^8 to 10^{10} hydrogen molecules per cubic centimeter and the temperatures greater than about 500 K to provide the necessary rate of excitation. To yield the observed intensities, path lengths of 10^{13} to 10^{15} cm are needed, which imply masses in the range of 10^{-7} to 10^{-3} times that of the sun for roughly spherical clumps. One explanation for the excitation of the maser emission is that it results from collisions of dense, fast-moving clumps of material with dense shells of ambient gas (*13*). Such a process accounts for the frequently observed coincidence of emission at both high velocity and at the radial velocity of the ambient medium. In the most energetic regions, hundreds of these objects are observed, and they carry considerable mass and kinetic energy (*11*). Understanding the detailed dynamics of these clumps is a current challenge for astrophysical theory.

Although water vapor maser emission is detected toward young stars of both high and low luminosity, it is weaker and there are fewer spots seen toward a given region for stars of lower luminosity (*14*). Because there are fewer maser spots near low-luminosity stars, it has not been possible to measure those masers' transverse motions from a sequential study of their juxtaposition by means of VLBI techniques. Nevertheless, it is conceivable that the radial motions inferred from Doppler shifts correspond to real space motions, as they do for the more luminous sources. It is then evident that the masers are participating in the molecular outflows observed in the CO emission. Typical radial velocities of the masers with respect to the clouds of gas in which they are found are 20 to 50 km/sec. To account for the emission of the masers, even the weaker ones associated with the lower luminosity stars, the masses of the masers must be at least about 10^{-7} times that of the sun. It is difficult to understand how a star whose mass is similar to that of our sun and whose early stellar luminosity is not more than ten times that of the present sun can loft such a projectile at up to 50 km/sec.

Herbig-Haro Objects

These wispy nebulosities were first recognized in photographs of the surfaces of dark dust clouds about 30 years ago (*3*). They appear as knotty condensations, emitting in the hydrogen Balmer lines and low-excitation lines of other abundant atoms such as oxygen and nitrogen. Their spectra typically show Doppler shifts corresponding to radial velocities of 100 to 200 km/sec; these velocities are usually negative, implying that the objects are coming toward us from the clouds. Three examples are shown in Fig. 1. Carbon monoxide outflows are typically associated with these objects. Measurements of the positions of some of these objects over several epochs show transverse space velocities comparable to the implied radial velocities (*15*). Objects HH28 and HH29 (Fig. 1) appear to be moving rapidly away from a point close to (perhaps coincident with) the embedded infrared star, which also appears to be the source of the CO outflows (*16*).

The nature of their spectra suggests that the emission results from the shock excitation associated with the collision of one rapidly moving parcel of gas with another (*17*). The rapid variability of the brightness of these objects is further evidence of the interaction of gas flowing through an irregular medium (*15*). Observations of HH1 and HH2 in NGC 1999 show that the brightest parts of the knots are on the side away from the apparent exciting star (the Cohen-Schwartz star), indicating that the shocked region is on the outward side of the knot and that the Herbig-Haro objects are in rapid motion, plowing into the surrounding cloud (*18*).

The objects emit substantial amounts of ultraviolet radiation (*3*). Their overall luminosity is sometimes as high as that of our sun, and the mass of radiating gas is typically about 10^{-6} that of the sun. The total mass of the object, including the neutral component, could be 100 times greater or more.

Like the H_2O masers, the Herbig-Haro objects appear to be small, massive "bullets" (*19*) moving at high speeds away from young stars. They are associated with both the CO outflows and the more extended, shock-excited 2-μm radiation from molecular hydrogen. Because it is not likely that a tenuous wind can gradually accelerate such dense condensations to their observed speeds (*20*), it is probable that they are somehow set into high speed close to their exciting stars. They are then observed when they collide with dense material at some distance from their source, perhaps when they collide with the wall of the cavity evacuated by the wind, producing the characteristic shock-excited emission.

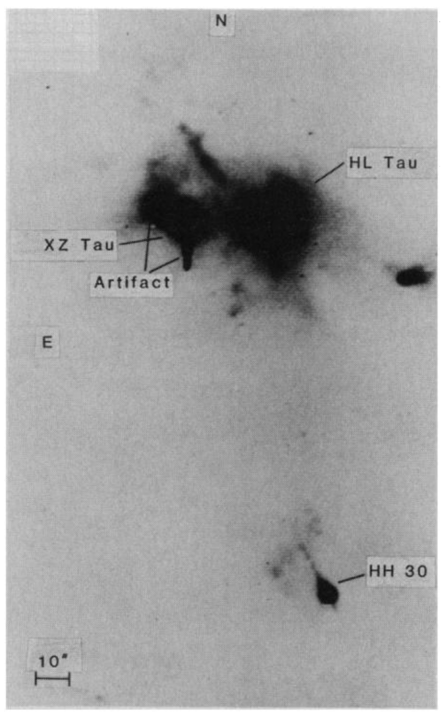

Fig. 2. An optical charge-coupled device (CCD) picture of the variable stars XZ Tau and HL Tau and of HH30, taken with a filter that transmits emission lines of hydrogen, oxygen, nitrogen, and sulfur. The artifact is due to charge overflow in the CCD. An image taken with a filter that excludes the emission lines shows a star within HH30. The jets on the two sides of HL Tau are parallel to, but not in line with, the jets of HH30. [From Mundt and Fried (*23*), courtesy of *Astrophysical Journal*]

The Central Stars

The key to the molecular jets must, of course, lie with the central stars. The candidates appear to be pre–main sequence stars, objects that have not yet reached the stable phase of hydrogen burning with a standard temperature and luminosity fixed by the stellar mass. These young stars range from the highly luminous, massive objects deeply embedded in the material from which they have formed (or are still forming) to the more numerous, low-mass T Tauri and related stars, some of which are visible in optical photographs in the outer regions of the interstellar clouds.

The T Tauri stars seem to be the precursors of stars that have masses within a factor of 2 or 3 of that of our sun (*21*). Their present luminosities range from 1 to 50 times that of the sun. In addition, they exhibit energetic winds, detected mostly in line emission from hydrogen, with velocities up to 400 km/sec and mass flows that, although uncertain, may be as high as 5×10^{-7} solar masses per year. The mechanical luminosity (the flow of kinetic energy) of a wind with these two features is about 12 times the radiative luminosity of the sun. Both the winds and the radiation vary substantially on time scales as short as a few years. The absorption and emission features in the stars' spectra are complex, and their interpretation is uncertain.

The most exciting discovery about the T Tauri stars is that several exhibit well-collimated jets both in the radio continuum (*22*) and in optical pictures taken in emission lines (*23*). The jets have small opening angles (5° to 10°) and are unresolved in their transverse dimensions close to the stars. They are well aligned with their associated Herbig-Haro objects and the larger scale CO flows. Also, they are evidently collimated close to the stars, on scales less than 3×10^{15} cm, and they have spectra similar to those of Herbig-Haro objects, which is characteristic of shock excitation. The brightness contours (6-cm wavelength) of the small radio source coincident with the central star in L1551 (Fig. 1, inset) are well aligned with the CO lobes. Figure 2, an optical picture of two T Tauri stars, XZ Tau and HL Tau, and of HH30 (*23*), shows highly collimated jets. The jets from both HL Tau and HH30, which evidently contains its own young star, are nearly parallel but not aligned. That they are not aligned suggests that the two objects are not directly connected; that they are parallel argues both that there is an overall preferred direction in the region and that the formation of the jets is related to it. This direction could be either that of a magnetic field or that of the angular momentum of the parcel of material from which the stars formed (or both). The large-scale magnetic field in the region of L1551 (Fig. 1) is parallel to the bipolar lobes (*5*).

Weak thermal radio continuum emission from ionized gas is also observed from the more luminous central objects (*14, 24*). If the wind is assumed to be fully ionized near the star by ultraviolet radiation from the star, then a wind whose strength is too small to account for the CO lobes can be inferred. However, the wind is unlikely to be fully ionized near the star if the more massive stars are at all like the T Tauri stars. The observed jets close to the stars are probably mostly neutral material, which is undetected by the radio telescope, and could have enough strength to power the CO lobes.

The collimated jets are different from the apparently spherical, high-velocity winds of the OB stars, the hottest of the hydrogen-burning stars. The OB star winds are satisfactorily explained as evaporated gas driven away from the hot stellar surface by radiation pressure (*25*). For the collimated flows it is not clear whether the material leaves the surface of the young star in two opposite directions, leaves the star isotropically and is then collimated by the surrounding medium, or does not come from the star but rather is accelerated away from some structure in the near neighborhood of the star. Disks around the central stars, which have formed as part of the process of protostellar collapse, have been proposed for either the second or third mechanism above (*26, 27*). Indeed, there is evidence for flattened, rotating disks around the central stars of many of the CO flows, with their rotation axes parallel to the flow directions (*28*). For example, IRS-5, the central star of L1551, shows the strong optical polarization expected of a flattened structure, perpendicular to the jet, that is scattering light from a central source (*29*).

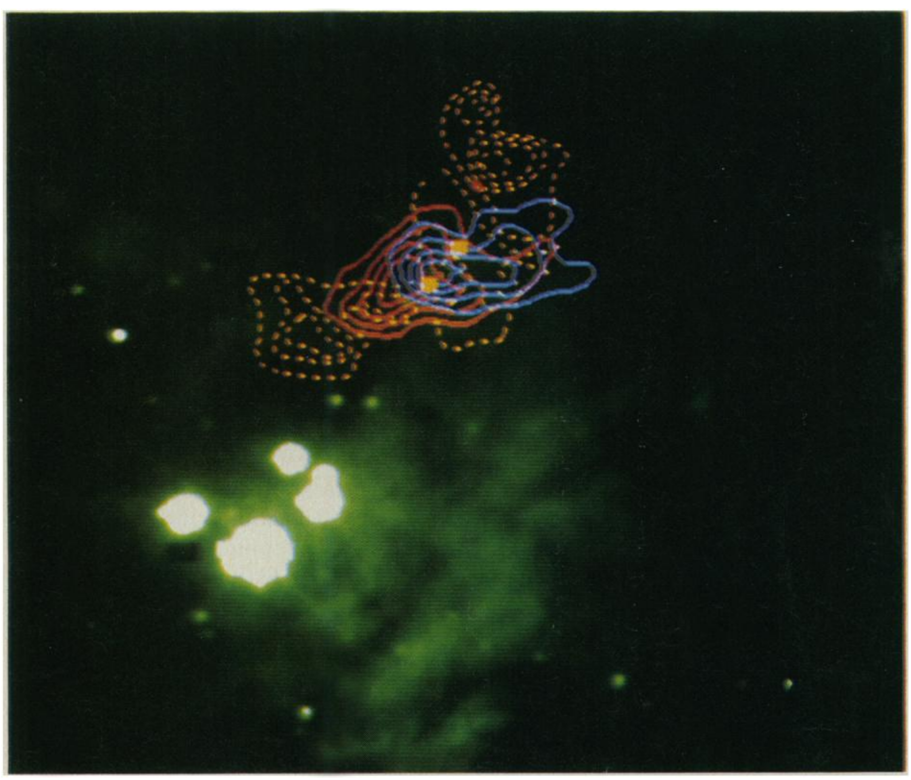

Fig. 3. Contour line in molecular emission (upper right); optical CCD image of the Trapezium cluster in Orion taken at the Lick Observatory. The orange squares are the BN and IRc2 infrared sources. The dotted yellow contours show the 2-μm wavelength emission from molecular hydrogen [from Beckwith *et al.* (*7*)]. The blue and red contours show, respectively, the blue-shifted and red-shifted outflows from IRc2 observed in SiO with the Hat Creek Millimeter Interferometer [from Wright *et al.* (*37*)]. Optical CCD image by S. Djorgovski.

The Orion Region

The best-studied outflow is associated with the KL infrared nebula in Orion, where molecular lines are especially strong and broad. More powerful outflows are observed in W49, W51, and Sgr B2, but these regions are located more than an order of magnitude farther away. The closeness of Orion (1500 light years) permits higher spatial resolution and signal-to-noise ratios than are possible with other massive star–forming regions. The construction of large millimeter-wavelength telescopes has made it possible to study the molecular line emission with resolutions of about 0.5 arc minute (*30*). Millimeter interferometers and the Very Large Array now permit mapping of lines with a resolution of a few arc seconds. The Orion outflow is located about 0.4 light year (1 arc minute) in projection to the northwest of the Trapezium, the cluster of young OB stars that excites the M42 ionized region. Figure 3 is an optical picture of the Trapezium cluster with isointensity contours of molecular emission associated with the outflow from the deeply embedded infrared nebula in the background (*7, 31*).

The KL region was first detected as an infrared nebula extending over about 0.5 arc minute with several emission peaks (*32*). Two compact infrared sources in KL, BN and IRc2, are stars of high mass at an earlier stage of evolution than the Trapezium that are still deeply embedded in molecular material (see Fig. 3). The other infrared peaks may be lower luminosity stars, dense young clumps of gas heated by BN and IRc2, or just holes in the cooler foreground dust distribution (*33*). The larger scale distribution of molecular gas is arranged in a ridge running northeast to southwest that is part of a giant molecular cloud extending for more than 200 light years. The radial velocity of the gas along the ridge shows a shift at the position of the KL region that has been interpreted as either rotation seen edge-on around the KL region or as the collision of two clouds of different radial velocities (*34*). The former interpretation suggests that the ridge is the result of a larger structure that has collapsed preferentially along its axis of rotation. Whatever the significance of the larger scale motions may be, the distribution of radial velocity close to the KL nebula corresponds to the motions of gas orbiting about a central condensation of material with a mass more than 20 times that of our sun (*35*).

The outflow from the Orion-KL region is one of the most energetic of the outflow sources that have been studied in any detail. The mechanical luminosity is close to 3000 times the radiant luminosity of the sun (*6*). Wind velocities of over 100 km/sec are inferred, and rates of mass loss of 3×10^{-3} to 7×10^{-3} solar masses per year are estimated to explain the intensity of infrared emission from molecular hydrogen and neutral atomic oxygen (*36*).

The source of the outflow appears to be IRc2, which is in the center of symmetry of the molecular line maps. Its importance relative to the BN source was shown by the water másers' movement away from it (*12*) and by the orientation of the polarization of infrared radiation scattered by its surroundings (*33*). Furthermore, its apparent luminosity is consistent with the mass derived from rotation as discussed above. Infrared observations show that the KL nebula is a clumped shell surrounding a cavity (*33*). Observations in the emission of SO (at 3.4-mm wavelength) show that the dense, clumped nebula is expanding away from IRc2 at a velocity of about 20 km/sec, presumably because it is material swept up in the wind from IRc2 (*37*). This shell is being driven into the ridge. The density decreases perpendicular to the major axis of the ridge, and consequently the outflow has ruptured the cavity walls in these directions, allowing the wind to escape. The plane of the ridge appears inclined to the line of sight. The diameter of this extended flow is larger than the shell by roughly a factor of 3. The red and blue lobes in Fig. 3 represent SiO molecules moving at high velocity away from IRc2 in a bipolar flow. The dotted contours correspond to the emission of molecular hydrogen, which is excited in shocks as the outflow collides with the ambient gas (*7, 37*).

Evidence for outflow in Orion exists on scales from 35 astronomical units (the SiO $v = 1$ masers close to IRc2) to 0.4 light year (the extended flow), a range of nearly three orders of magnitude. Taking a characteristic time t equal to length divided by velocity, we find that t ranges from 10 years for the masers close to IRc2 to 1000 years for the extended outflow (*12*). Clearly, the outflow is not the result of a single explosion, although it is uncertain whether the present rate of outflow is as large as the rate derived for the large-scale flow. The H_2O masers, which are moving away from IRc2, are found both in the dense shell and in the regions of molecular hydrogen emission in the extended flow. Also, their motion is not well collimated close to the central star. Apparently, in the Orion region, the collimation of the extended flow into approximately bipolar lobes is a result of the flattened ridge distribution. Figure 4 is an idealization of the outflow from IRc2 and its effect on its surroundings. Although the wind is depicted as leaving the central star, it may actually be accelerated away from a disklike structure near the central star.

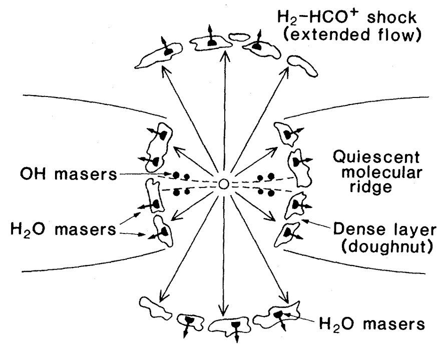

Fig. 4. A model of the KL infrared nebula in Orion as it would be seen edge-on to the large-scale ridge of gas. The central object is IRc2. The dense, clumped layer of swept-up gas is the infrared nebula, seen also in maps of SO and HCN at Hat Creek. The extended flow results from the wind escaping normal to the ridge in directions where the density drops off more rapidly. Water vapor maser emission occurs where dense clumps in the wind collide with the shell of swept-up gas or with clumps in the extended flow. The wind is shown flowing from IRc2 isotropically, but it may instead be accelerated away from a disk, shown by the dotted lines. In this model, the wind is collimated by the ridge.

Molecular abundances in outflows are known to be markedly different from those in quiescent clouds. The outflow velocities are supersonic, which leads to shocks, and shocks can greatly affect abundances by (i) destroying existing molecules; (ii) destroying dust grains, which greatly increases the fractional abundance of heavy atoms in the gas; (iii) driving exothermic reactions that require high temperatures; and (iv) changing the ionization fraction. Even the abundance of CO is predicted to be enhanced, and this has been observed in the Orion outflow (*38*). High angular resolution interferometer maps of Orion-KL in a number of different lines show that molecular abundances vary by orders of magnitude even within a small portion of the outflow region (*39*). Accordingly, any interpretation of observations that average over an entire outflow region should be viewed with caution.

Figure 5 shows interferometer maps of three molecules: bicarbonate ion, hydrogen cyanide, and silicon monoxide. The outer contours of the HCO^+ map match those of the shock-excited H_2 well, showing that they are closely related. The HCN map is essentially identical to that of SO and provides again a picture of the dense shell of swept-up gas. Typical resolution in the maps is about 5 arc seconds. The abundance ratio of HCN to HCO^+ decreases by two or three orders of magnitude from the shell to the extended flow. In the shell, the abundance ratio of HCN to H_2 is 5×10^{-7}, several orders of magnitude higher than in quiescent clouds, whereas the abundance of HCO^+ is not appreciably enhanced. The high abundance of HCN can be explained by shock models in which destruction of the dust mantle is included. The variation in the ratio of HCN to HCO^+ is probably partly due to changes in the abundance of the latter. The formation of HCO^+ requires reactions between ions and molecules even in a shock, which means that the HCO^+ abundance is directly related to the ionization fraction. The density is higher in the shell than in the extended flow, so the recombination rate is higher. Also, the column density is higher in the shell, which results in greater attenuation of x-ray flux from the Trapezium and other local x-ray sources. Both effects contribute to a lower ionization fraction in the shell than in the extended flow. Abundances of HCO^+ vary among outflow sources, which might be explained by similar variations in density and x-ray and ultraviolet flux.

Emission of SiO is substantially more compact than emission from any other molecule mapped at high resolution; it has mainly been detected near outflows in star-forming regions (*39, 40*). At the high temperatures characteristic of shocks, much of the gas-phase Si is expected to be processed into SiO; because the cosmic abundance of Si is 10^{-5}, a very high molecular abundance might result. Normally, however, Si is highly depleted onto dust grains. In shocks of 50 to 100 km/sec, the larger grains are destroyed (*41*), and consequently the abundance of gas-phase Si is increased. Shocks of this speed dissociate the molecules, but because the small grains (which have most of the surface area) remain, H_2 can reform quickly. SiO can then form, with an abundance far higher than in quiescent clouds. Then it is quickly depleted onto grains, so that the enhancement does not persist for long; therefore, the emission is relatively compact. Clearly, SiO is an excellent probe of high-velocity shocks.

Possible Wind Mechanisms

It is unlikely that the radiant luminosity of the central star directly drives the outflow (*6*). The momenta in the outflows are in the range of 10 to 1000 times

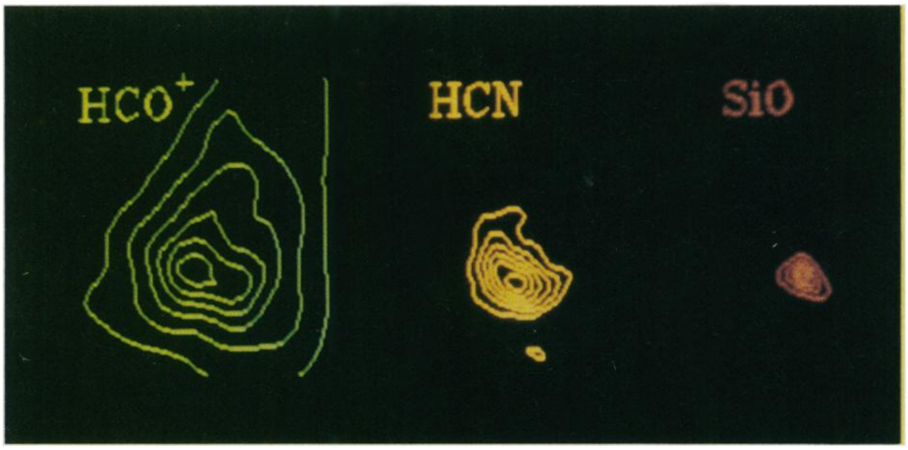

Fig. 5. Interferometer maps of HCO^+, HCN, and SiO, each centered on IRc2. All velocities are included except for the narrow component associated with the quiescent surrounding cloud. Except for the faint high-velocity wings, the SiO is very compact, lying within 5 to 10 arc seconds of IRc2. The HCN, extending for 20 arc seconds, outlines the swept-up shell of gas and is unobserved outside. The HCO^+ extends over about 2 arc minutes, coinciding with the region of H_2 emission in the extended flow [from (*35, 37, 39*)].

that of the radiation. For the radiation pressure to accelerate material to such large momenta requires that the *e*-folding absorption or scattering length in the outwardly driven material be 0.1 to 0.001 of the actual thickness of the material. Evidence from observations indicates that the column depths of the outflowing material are much smaller than this.

The similarities between the outflows of the low and high luminosity sources are greater than their differences. The time scales are comparable. Both have dense clumps in the form of H_2O masers and Herbig-Haro objects (*14, 42*). Both show a range of collimations in their flows. Most important, there is only a weak positive correlation between the radiant luminosities of the central stars and the luminosities of the outflows (*6*). There is also a large scatter in this correlation, with some objects of low radiative luminosity having flow luminosities comparable to those of objects that radiate more by two to three orders of magnitude. Some of the scatter may be due to the semitransient nature of the outflows. However, the weak correlation suggests that whatever powers the outflows is not proportional to the radiative luminosity of the central object. It was noted above that the momentum in the radiation from the central stars is generally too small to accelerate the flows.

Two conclusions may be drawn. The first is that the mechanism for acceleration of the winds is probably the same for both the high and low luminosity objects. The second is that the wind luminosity increases slowly with the mass of the central star, perhaps only in direct proportion. The range of masses of stars more massive than the sun is only two orders of magnitude compared to the range of luminosities, which is nearly six orders of magnitude. For the outflow luminosity to be approximately proportional to mass rather than to radiant luminosity suggests that it may depend on the energy of rotation of the collapsed object. Ideally, an explanation for the outflow phenomenon should have the following features. The mechanism should be qualitatively the same for all stars as massive as the sun or greater. It should take into account the local magnetic field or angular momentum (or both). Approximately all stars as massive as the sun should go through this phase, and it should last for 1,000 to 100,000 years. Flow luminosities up to a few thousand times the radiant luminosity of the sun must be produced, and the dependence of mechanical luminosity on mass must not be steep.

Although there have been a number of suggestions and a few detailed models put forward, there is as yet no generally accepted explanation for the outflows. There are two classes of explanations. One argues that the winds or flows come directly from the central stars; the other suggests that the material is accelerated in the near neighborhood of the star. In the first class of mechanisms there have been two proposals. In a low-mass protostar, the onset of deuterium burning is expected to redistribute the angular momentum within the star, releasing a strong pulse of mechanical energy (*43*). Alternatively, there may be a sudden heating of the stellar surface due to an instability associated with rapid rotation during collapse (*44*). If the resulting outflows from the stars are isotropic, then they could be collimated by either anisotropic density or pressure distributions in the surrounding media (*26*). The T Tauri star winds are observed to be collimated within a distance of less than 10^{15} cm from the star.

Several versions of the second kind of mechanism have been proposed, all of which rely on an interstellar magnetic field to transfer energy of rotation from the collapsed protostellar object to a bipolar outward moving gas (*27*). In some cases a disk around the young star takes part. There is ample evidence for both disks and magnetic fields, making these models attractive. The present state of the evidence does not clearly favor any one of these models.

Conclusions

The stellar winds in the clouds from which stars form may have a profound effect on the physical evolution of these clouds. Broad molecular emission lines corresponding to local supersonic motions are typically observed from extensive regions of active clouds. It is possible that protostellar winds stir up large regions of the clouds, increasing the pressure and inhibiting further collapse (*45*). In this way the winds regulate both the rate of star formation and the lifetimes of the clouds. Because of their large number and comparable wind strengths, the low-mass T Tauri stars and related objects are likely to have the greatest effect (*10*).

High-resolution observations in the Orion-KL region reveal a high degree of chemical processing associated with the shocks produced by the winds. There are significant abundance gradients. Sulfur-bearing compounds are strongly enhanced, for example, and may be entirely produced by shock chemistry. Although ion-molecule reactions must be important in the overall production of molecules, it may be that shock chemistry plays a comparable role.

Because the outflow phenomenon appears to be a phase through which all protostars pass, it may have some bearing on a remaining puzzle about star formation: What determines the mass of a star? The onset of the outflow may stop further accretion onto the protostar and fix the mass of the star (*43*). An understanding of what triggers the outflow may also provide an answer to the puzzle. But the question remains: What produces the jets? In some ways these molecular jets resemble the highly energetic outflow phenomena in radio galaxies (*46*). Similar mechanisms have been proposed for the collimation. Because the molecular jets are closer at hand, there is a greater opportunity to study and understand them.

References and Notes

1. D. M. Rank, C. H. Townes, W. J. Welch, *Science* **174**, 1083 (1971); P. M. Solomon, *Phys. Today* **26**, 32 (1972).
2. R. Genzel and D. Downes, *Astron. Astrophys. Suppl.* **30**, 145 (1977).
3. G. H. Herbig, *Astrophys. J.* **111**, 11 (1950); G. Haro, *ibid.* **115**, 572 (1952); R. D. Schwartz, *Annu. Rev. Astron. Astrophys.* **21**, 209 (1983).
4. A. A. Penzias, K. B. Jefferts, R. W. Wilson, *Astrophys. J.* **165**, 229 (1971); B. Zuckerman, T. Kuiper, E. Rodrigues-Kuiper, *ibid.* **209**, L137 (1976); J. Kwan and N. Scoville, *ibid.* **210**, L39 (1976).
5. R. Snell, R. Loren, R. Plambeck, *ibid.* **239**, L172 (1980).
6. L. F. Rodriguez, P. Carral, P. T. P. Ho, J. M. Moran, *ibid.* **206**, 635 (1982); J. Bally and C. J. Lada, *ibid.* **265**, 824 (1983); P. F. Goldsmith, R. L. Snell, M. Hemeon-Heyer, W. D. Langer, *ibid.*, in press.
7. D. Nadeau, T. R. Geballe, G. Neugebauer, *ibid.* **253**, 154 (1982); T. Simon and R. R. Joyce, *ibid.* **265**, 864 (1983); S. Beckwith, S. E. Perrson, G. Neugebauer, E. E. Becklin, *ibid.* **223**, 464 (1978).
8. R. L. Snell, N. Z. Scoville, D. B. Sanders, N. R. Erickson, *ibid.* **284**, 176 (1984).
9. M. Ferking and W. Langer, *ibid.* **256**, 523 (1982); R. Snell, and S. Edwards, *ibid.*, in press.
10. S. Beckwith, A. Natta, E. E. Salpeter, *ibid.* **267**, 596 (1983).
11. R. Genzel and D. Downes, *Astron. Astrophys.* **78**, 239 (1979).
12. R. Genzel, M. J. Reid, J. M. Moran, D. Downes, *Astrophys. J.* **244**, 884 (1981).
13. J. Tarter and W. J. Welch, *ibid.*, in press.
14. G. Sandell and H. Olofsson, *Astron. Astrophys.* **99**, 80 (1981); A. Haschick, J. M. Moran, L. Rodriguez, P. T. P. Ho, *Astrophys. J.* **265**, 281 (1983); J. M. Moran, *Rev. Mex. Astron. Astrophys.*, in press.
15. G. H. Herbig and B. F. Jones, *Astron. J.* **86**, 1232 (1981).
16. K. M. Strom, S. E. Strom, F. J. Vrba, *ibid.* **81**, 320 (1976); C. Beichman and S. Harris, *Astrophys. J.* **245**, 589 (1981).
17. R. D. Schwartz, *Astrophys. J.* **195**, 631 (1977); M. A. Dopita, *Astrophys. J. Suppl.* **37**, 117 (1978).
18. L. Hartman and J. C. Raymond, *Astrophys. J.* **276**, 560 (1984); S. U. Choe, K. H. Bohm, J. Soff, *ibid.*, in press.
19. C. Norman and J. Silk, *ibid.* **228**, 197 (1979); L. Rodriguez, J. M. Moran, P. T. P. Ho, E. W. Gottlieb, *ibid.* **235**, 845 (1980).
20. M. T. Sanford and R. W. Whitaker, *Mon. Not. R. Astron. Soc.* **205**, 105 (1983).
21. L. V. Kuhi, *Astrophys. J.* **140**, 1409 (1984); S. Strom, K. Strom, G. Grasdalen, *Annu. Rev. Astron. Astrophys.* **13**, 187 (1975); M. Kutner, C. M. Leung, D. E. Machnik, K. N. Mead, *Astrophys. J.* **259**, 35 (1982).
22. J. Bally and N. Z. Scoville, *Astrophys. J.* **255**, 497 (1982); M. Cohen, J. Bieging, P. R. Schwartz, *ibid.* **253**, 707 (1982).
23. R. Mundt and J. Fried, *ibid.* **274**, L83 (1983); R. Mundt, J. Stocke, H. S. Stockman, *ibid.* **265**, L71 (1983); M. Cohen and R. D. Schwartz, *ibid.*, p. 877.
24. J. Bally and R. Predmore, *ibid.*, p. 778; J. M. Moran, G. Garay, M. J. Reid, R. Genzel, *Bull. Am. Astron. Soc.* **15**, 989 (1983).
25. J. Cassinelli, *Annu. Rev. Astron. Astrophys.* **17**, 275 (1979).
26. A. Konigl, *Astrophys. J.* **261**, 115 (1982); J. Canto and L. Rodriguez, *ibid.* **239**, 982 (1980).
27. B. T. Draine, *ibid.* **270**, 519 (1983); Y. Uchida and K. Shibata, in *Non-radiative Energy Momentum in Hot Stars*, A. Underhill, Ed. (NASA, Washington, D.C., in press); R. Pudritz, *ibid.*
28. J. Bieging, *Astrophys. J.*, in press; T. Takano *et al.*, *ibid.* **282**, L69 (1984); M. Cohen, *Publ. Astron. Soc. Pac.* **94**, 266 (1982).
29. T. Nagata, S. Sato, Y. Kobayashi, *Astron. Astrophys.* **119**, L1 (1983).
30. O. E. H. Rydbeck, A. Hjalmarson, G. Rydbeck, J. Ellder, H. Olofsson, A. Sume, *Astrophys. J.* **243**, L41 (1981); P. Solomon, G. Huguein, N. Scoville, *ibid.* **245**, L19 (1981).
31. M. C. H. Wright, R. L. Plambeck, S. N. Vogel, W. J. Welch, P. T. P. Ho, *ibid.*, in press.
32. G. H. Riecke, F. J. Low, D. E. Kleinmann, *ibid.* **186**, L7 (1973).
33. C. G. Wynn-Williams, R. Genzel, E. E. Becklin, D. Downes, *ibid.* **281**, 172 (1984); M. W. Werner, H. L. Dinerstein, R. W. Capps, *ibid.* **265**, L19 (1983).
34. P. T. P. Ho and A. H. Barrett, *ibid.* **224**, 223 (1978); P. Bastien *et al.*, *Astron. Astrophys.* **98**, L4 (1981).
35. S. N. Vogel, J. H. Bieging, R. L. Plambeck, W. J. Welch, M. C. H. Wright, *Astrophys. J.*, in press.
36. M. W. Werner, M. K. Crawford, R. Genzel, D. J. Hollenbach, C. H. Townes, D. M. Watson, *ibid.* **282**, L82 (1984).
37. R. L. Plambeck *et al.*, *ibid.* **259**, 617 (1982); M. C. H. Wright, R. L. Plambeck, S. N. Vogel, P. T. P. Ho, W. J. Welch, *ibid.* **267**, L41 (1983).
38. W. D. Watson and C. M. Walmsley, in *Regions of Recent Star Formation*, R. S. Roger and P. E. Dewdney, Eds. (Kluwer Academic, Hingham, Mass., 1982), p. 357.
39. S. N. Vogel, M. C. H. Wright, R. L. Plambeck, W. J. Welch, *Astrophys. J.* **283**, 655 (1984).
40. D. Downes, R. Genzel, A. Hjalmarson, L. A. Nyman, B. Ronnang, *ibid.* **252**, L29 (1982).
41. G. F. Mitchell and T. J. Deveau, in *Regions of Recent Star Formation*, R. S. Roger and P. E. Dewdney, Eds. (Kluwer Academic, Hingham, Mass., 1982), p. 107.
42. D. J. Axon and K. Taylor, *Mon. Not. R. Astron. Soc.* **207**, 214 (1984).
43. F. Shu, *Int. Astron. Union Symp.* **106**, 561 (1984).
44. R. B. Larson, *Mon. Not. R. Astron. Soc.* **109**, 321 (1980).
45. C. Norman and J. Silk, *Astrophys. J.* **238**, 158 (1980).
46. D. S. de Young, *Science* **225**, 677 (1984).
47. J. H. Bieging and M. Cohen, *Astrophys. J.*, in press.

RESEARCH ARTICLE

Long-Term Ecosystem Stress: The Effects of Years of Experimental Acidification on a Small Lake

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Ecologists believe that both natural and anthropogenic stresses cause changes in ecosystems that cannot be deduced from effects on individual species or populations because of the deterioration of ecosystem structure and function (*1*). The degree of such "ecosystem-level" responses to anthropogenic stresses, and the degree to which ecosystems can recover after the stresses are removed, are subjects of fundamental importance to natural resource management (*2*), yet only a few studies have been able to quantify the causes and effects of stresses on whole ecosystems (*3, 4*). Reasons for this include the following: (i) The ecosystems were too large or complex to study in their entirety. (ii) Documentation of ecosystem structure, function, and natural variation prior to anthropogenic stress was inadequate. (iii) Individual stresses could not be quantified, or effects of one perturbation on the ecosystem could not be isolated from other stresses (*5*).

We were able to overcome many of these problems in an ecosystem-scale experiment in Lake 223, a small Precambrian Shield lake surrounded by virgin boreal forest in the Experimental Lakes Area, and typical of poorly buffered small lakes of northwestern Ontario (*6–9*). Over a period of 8 years, the *p*H of the lake has been gradually decreased from 6.8 to 5.0 by the addition of sulfuric acid. Our studies revealed various apparent mechanisms of response of the lake's biota to increased acidity, ranging from direct toxicity of hydrogen ion to disruptions of normal food-chain relations, behavioral patterns of animals, and biogeochemical cycles in the lake. In some cases, synergistic interactions of several stresses appeared to be involved. Some of the adverse changes occurred much earlier in the acidification process (that is, at higher *p*H) than is commonly believed to cause ecosystem degradation. This suggests that early ecological damage from lake acidification may be more extensive than was previously believed, a result that should be of vital interest to agencies regulating the emission of acid precursors. Other effects were so subtle or so complex that they might have been undetected in a system less thoroughly studied. In this article, we summarize the biological results of the first 8 years

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