CO OUTFLOWS FROM YOUNG STARS

BO REIPURTH
European Southern Observatory
Casilla 19001, Santiago 19, CHILE

AND

RAFAEL BACHILLER
Centro Astronómico de Yebes
Apartado 148, 19080 Guadalajara, SPAIN

1. General Properties of CO Outflows

Following the detection of extended CO wings in Orion A by Kwan & Scoville (1976) and Zuckerman et al. (1976) came the discovery in 1980 of the first bipolar CO outflow from a low luminosity source, L1551 IRS 5 (Snell, Loren, Plambeck 1980). It was soon realized that bipolar outflows are common in star forming regions, as documented in a highly influential paper by Bally & Lada (1983), and a series of papers by Edwards & Snell (1982, 1983, 1984). Many of the presently best studied molecular outflows were already identified in these early papers, and it was established that there is an association between the optically emitting shocks seen as Herbig-Haro objects and the large-scale moving CO gas. Further details of the early years of molecular outflows are discussed by Lada (1985).

Molecular outflows are commonly found in regions of active star formation, and it is probable that all newborn stars must pass through a phase of prodigious mass loss. Indeed, there is evidence that mass loss may begin already in the protostellar phase, as soon as a stellar core has started to build up. CO outflows are interpreted as the effect of this mass loss on the ambient molecular material, which is gradually being swept up.

Most CO outflows are bipolar, although a few unipolar or amorphous flows are known. Collimation factors typically range from 2 to 5, but recent higher resolution observations have uncovered several much more collimated flows (e.g., Richer et al. 1992). It is also becoming increasingly evident that the lobes of CO outflows are not uniform, but show a clumpy structure (e.g., Bachiller et al. 1994), which suggests that the driving sources may undergo episodic eruptions.

The sizes of CO outflows range from a few tenths of a parsec to about 5 parsec, with masses from less than a solar mass to more than 100 $M_\odot$; there is some tendency for the more massive flows to be driven by higher luminosity sources (Bally & Lada 1983). Such massive flows exclude the possibility that they originate from the embedded stars. Rather, these outflows must consist of swept-up ambient material. Velocities are for most of the outflowing material only a few $\mathrm{km\,s^{-1}}$, but very high velocities of more than 100 $\mathrm{km\,s^{-1}}$ have been found in highly collimated "molecular jets" (see Sect. 3).

2. CO Outflows and Herbig-Haro Flows

An essential question is: How are CO flows driven? The interaction between the driving agent and the ambient molecular material can be either adiabatic or radiative. In the first case the flow is energy driven by the expansion of a high-pressure bubble. In the second case it is momentum driven, with momentum being transferred via entrainment (Dyson 1984).

It is becoming increasingly clear that CO flows, at least from low-mass sources, are momentum driven, and are accelerated by Herbig-Haro jets. Already in the early work of Edwards & Snell (1983,1984), it was realized that the two phenomena often co-exist. However, the low estimates of momentum rates of HH flows by Snell et al. (1985) and Mundt et al. (1987) appeared to suggest that they were not capable of producing the momentum observed in CO flows. In a more sophisticated analysis, Raga (1991) has shown that the two flow phenomena have the same mass and momentum rates, and that a "unified" flow model is viable. A number of theoretical models have explored the details of how the momentum transfer occurs. It appears that we are right now seeing a paradigm shift from the belief that CO flows and HH flows are two aspects of the same underlying process (winds), to the view that CO flows are the direct results of HH jets ramming through ambient molecular material.

HH jets are generally highly collimated, with collimation factors of up to 100. They are very narrow, with angular widths of less than 1 arcsec, and physical widths of a few hundred AU. They almost always emanate from deeply embedded low-luminosity sources, and have space velocities of several hundred $\mathrm{km\,s^{-1}}$. They consist of chains of small knots, which are interpreted as internal shocks caused by variations in the flow due to variability of the underlying source (Raga et al. 1990). Where the jet rams into the ambient medium a working surface is formed, which consists of two shocks, a bow shock where the ambient material is shocked and accelerated, and a jet shock, or Mach disk, where the jet material is decelerated. It is common to find multiple working surfaces along the axis of an HH flow, testifying to recurrent eruptions of the underlying source, probably FU Orionis accretion disk events (Reipurth 1989). The fact that the working surfaces normally have very high space velocities indicates that the jets are considerably more dense than their surroundings. For a recent review of the properties of HH jets, see, e.g., Reipurth & Heathcote (1993).

HH jets can transfer momentum to their surroundings in two different ways. In the *hard* interaction, gas is accelerated at the working surface at the head of the jet. Seen in a frame at rest with the working surface, material enters through both the bow shock and through the jet shock and is subsequently ejected sideways. In the *soft* interaction, lateral entrainment occurs along the boundary between the body of the jet and its environment. While both mechanisms are probably active, the principal momentum transfer is likely to occur at the working surface at the tip of the jet.

A fine example of a Herbig-Haro jet is HH 46/47, seen in Fig.1 in a combination of Hubble Space Telescope images taken through Hα and [SII] filters (Heathcote et al. 1996). The jet flows at several hundred $\mathrm{km\,s^{-1}}$ away from an infrared source (in the lower right corner) embedded in an isolated Bok globule. A large reflection nebula outlines a conical cavity in the globule, through which the jet is seen to escape. The jet itself consists of a long thin body of numerous knots and an extended working surface. The knots are meandering away from the source, and inspection of the individual interference filter images show that at each knot where the body of the jet has a change of direction, the knot, which is [SII] bright, drives an Hα strong shock into the ambient medium. Kinematically, this interaction causes the outer part of the jet to move slower relative to the inner part, as seen in the Fabry-Perot images of Hartigan et al. (1993). The wiggling of the jet is possibly due to precession of the driving source. As a result, the jet interacts with a larger volume of its environment than if it was straight.

The jet is presently entering the working surface at an angle, which accounts for the asymmetry of the working surface. The material ejected sideways from the working surface interacts with the ambient material that is streaming by, and a contact discontinuity with a turbulent mixing layer is formed. Theoretical models suggest that this hot layer expands and fills the cavity behind the working surface, forming a turbulent wake which may be observable as a molecular outflow (Raga & Cabrit 1993). Alternatively, the swept-up shell may itself be interpreted as the molecular outflow (Masson & Chernin 1993). The HST image of HH 46/47 shows a faint emission veil streaming backwards from the bow shock, and this is most likely direct observational evidence of the abovementioned interaction zone. In other words, *we here directly see a molecular outflow in the making.*

Figure 1. A Hubble Space Telescope image of the HH 46/47 jet complex, made by combining images taken through Hα and [SII] filters. From Heathcote et al. (1996).

The HH 46/47 jet is indeed observed to drive a CO outflow, albeit a small one (Chernin & Masson 1991, Olberg et al. 1992). Particularly the blue lobe, which coincides with the visible HH jet, is weak, simply because there is little molecular material left to sweep up. Massive luminous OB stars near the Bok globule have blown away the material which would normally obscure the jet. The HH 46/47 jet is thus unusual in the sense that we have the opportunity to directly watch the HH jet, which in most other cases are still deeply shrouded, and only detectable in near-infrared H_2 emission, if at all.

The best studied association between an HH jet and a CO flow is HH 111, a large highly collimated jet that drives a major molecular outflow

(Reipurth & Olberg 1991). The CO flow is also very collimated, and contains a number of "bullets" providing evidence of multiple ejection events in the source (Cernicharo & Reipurth 1996). IRAM interferometer observations at Plateau de Bure reveal that the base of the HH jet is surrounded by a tube of fast CO gas providing direct observational evidence for CO entrainment by an HH jet (Cernicharo et al. 1996).

3. Jet-driven CO Outflows: The Case of L 1448

The discovery of a new class of highly-collimated molecular outflows, which are similar in many respects to the optical HH jets, is providing much support for the new unified picture of molecular outflows and HH jets (e.g., Bachiller & Gómez-González 1992, Bachiller 1996).

The fast bipolar outflow in L 1448 is one of the best examples of highly collimated CO outflows (Bachiller et al. 1990). This is because the outflow is nearby (300 pc), and its axis is highly inclined (by about 70°) with respect to the line of sight. The CO profiles observed toward the outflow display a rich structure: in addition to the classical (smooth) CO line wings, there are "extremely-high-velocity" (EHV) peaks at radial velocities up to $\pm 70\ \mathrm{km\,s^{-1}}$. The EHV CO emission is located on the main outflow axis in the form of a narrow molecular jet which consists of a chain of very well defined clumps moving with space velocities in excess of $200\ \mathrm{km\,s^{-1}}$. These high-velocity molecular "bullets" have typical sizes of $\leq 15''$ (0.02 pc), masses of a few $10^{-4}\,M_{\odot}$, and exhibit strong SiO emission (Bachiller et al. 1991b, Guilloteau et al. 1992, Dutrey et al. 1996). High-velocity water maser spots have been observed to share the outflow motion in the proximity of the central young object (Chernin 1995). The central molecular jet is surrounded by a kind of thin H_2 envelope or cocoon which emits strong 2.12 μm lines (e.g. Bally et al. 1993; Davis et al. 1994), and that seems to be a near-IR counterpart of the classical HH flows observed in the visible. The H_2 emission is thought to arise in the mixing layer where the jet is entraining ambient molecular material.

The central jet in L 1448 is also surrounded by a more extended envelope of slow-moving CO, a "standard-high-velocity" (SHV) flow. Recent observations carried out at the IRAM interferometer on Plateau de Bure have revealed that this SHV CO emission arises in limb-brightened cavities with a biconical morphology (Bachiller et al. 1995a). The kinematical structure of the cavities is well accounted for with a model in which the CO moves on a narrow biconical shell with the velocity field parallel to the cone walls. Some near-IR continuum emission is observed to arise from the blueshifted part of the cavity (Bally et al. 1993). Very likely, this emission is produced by light escaping from the central object (L 1448-mm) which is scattered at the walls of the cavity through which the blueshifted flow emerges. Indeed we should expect another nebulosity to be formed at the southeast of L 1448-mm, but due to the inclination of the bipolar outflow, the receding lobe is more embedded within the ambient cloud, and the nebula formed at the redshifted CO lobe remains hidden by a higher intervening column density of dust. In summary, the configuration observed at the base of the L 1448 outflow suggests that we are witnessing the formation of a cometary nebula. As the outflow disperses more ambient material, the nebula will become optically visible giving a similar configuration to, for instance, Hubble's nebula illuminated by R Mon.

All the existing observations strongly suggest that the bipolar molecular outflow in L 1448 is being driven by the central fast jet which lies at the outflow axis. These observations, and those of similar objects (Bachiller & Gómez-Gónzalez 1992) have motivated a number of jet-driven models for molecular outflows (e.g. Richer et al. 1992; Raga & Cabrit 1993; Masson & Chernin 1993; Stahler 1994; Chernin et al. 1994a). Such models have allowed to make predictions about, e.g., the kinematics of the molecular gas (Stahler 1994), shapes of the flow lobes (Raga & Cabrit 1993), and other attributes of the molecular gas which can be observed now with the available instrumentation.

In all these models, a highly collimated jet injects mass and momentum into the surrounding ambient molecular clouds, but the assumptions differ from model to model. For instance, Stahler (1993) proposes that the standard CO outflow corresponds to a "turbulent envelope" in which the jet and entrained ambient material are mixed. However, one of the main problems faced by this kind of jet-driven models to explain the morphology of the L 1448 outflow (and most other highly-collimated outflows) is that the cavity observed at the base of the outflow is well developed, with typical opening angles of 30–45°. In other words, the ambient molecular gas is observed to be entrained over long transverse distances. In contrast, the mixing turbulent layer produced by the propagation of the highly supersonic jet is expected to be very narrow (Cantó & Raga 1991). This discrepancy could, in principle, be solved by allowing the direction of the jet to wander (Masson & Chernin 1993). Indeed, if a narrow jet wanders around a given direction, it will excavate a much larger area than in the case of a stationary jet. However, the existing observational evidence for precessing molecular jets (see, for instance, Gueth et al. 1996 for the case of L 1157) indicate that, when present at all, the precession happens in much narrower cones than those observed at the base of highly-collimated outflows.

Probably the most promising jet-driven models of bipolar molecular outflows are those in which the jet entrains ambient molecular material through the formation and propagation of large "bow shocks" which sweep up the ambient molecular gas (see Sect.2). In this kind of model, the jet is able to disturb the ambient gas at relatively large distances from the jet axis, which could explain the low collimation of most observed CO outflows. Moreover, such models are able to explain the formation of large cavities, and predict the geometrical form of the cavities by assuming that the characteristic size of the bow shock increases slowly with distance (see the simulations by Raga & Cabrit 1993). This occurs, for example, if the density of the surrounding ambient gas falls as a power law of index β in the range −4 to 0, but a similar behavior is obtained if the mass-loss rate or the ejection velocity from the working surface increases with distance from the source.

In the case of L 1448, strong support for a model in which successive bow shocks are responsible for the formation of the standard CO outflow, and the cometary nebula, comes from a comparison of the H_2 images of the jet (Bally et al. 1993) with the CO images of the cavity (Fig. 2). The walls of the cavity seen at blueshifted velocities are complementary to the bow shock traced by the H_2 emission, i.e., the arc structure delineated by the innermost blueshifted H_2 bow shock seems to "close" the conical CO cavity. This morphology clearly favors the jet-driven models based on entrainment of ambient material through the propagation of large bow shocks. A similar situation, with large bow shocks and biconical cavities, is also clearly observed in the L 1157 molecular outflow (Gueth et al. 1996).

However, not all the details are well accounted for by current models of gas entrainment by bow shocks. In particular, the shapes of the cavities observed in L 1157 are very difficult to reproduce. Also, as pointed out by Lada & Fich (1996), the velocity field over the length of the bow shock is very badly understood at present. Finally, detailed calculations produce outflow lobes which are narrower than the observed ones (e.g. Raga et al. 1993).

The source driving the L 1448 outflow, L 1448-mm, is an extremely cold object which has been detected at mm, cm, and FIR wavelengths (Bachiller et al. 1991a; Curiel et al. 1990); its spectral flux distribution points to an extremely young object, a "Class 0" source (André et al. 1993). It appears that most of the highly-collimated molecular outflows similar to L 1448 (e.g., IRAS 03282, NGC 2264G, L 1157, L 1527, VLA 1623, NGC 1333/IRAS 4, L 483) are driven by this kind of Class 0 source. Such sources are believed to be the youngest (proto-)stellar objects known at present, and have the peculiarity of being extremely efficient in transferring momentum to their associated molecular outflows. This extraordinary outflow activity, as well as other properties of Class 0 sources, is still far from being well understood.

Figure 2. Superposition of a grey-scaled H_2 image of the L 1448 jet (from Bally et al. 1993) and the CO images of the cavity observed with the IRAM interferometer (from Bachiller et al. 1995a).

4. The Role of Chemistry: L 1157

The shock waves generated by the high Mach-number jets from young stars propagate through the ambient molecular cloud and alter the physical conditions and the chemical composition of the gas. In particular, shock-processing of the dust grains leads to an injection of certain atoms and molecules into the gas phase. Particularly spectacular is the case of the refractory SiO molecule which is found to be enhanced by several orders of magnitude at the shocked regions of high-velocity outflows (Bachiller et al. 1991b; Martín-Pintado et al. 1992; McMullin et al. 1994). Sulfur-bearing molecules are also known to be enhanced (e.g., Chernin et al. 1994b).

The blueshifted lobe of the bipolar outflow in L 1157 is one of the best targets to study the region in which an outflow is interacting with the ambient medium. This lobe presents manifest signs of shock-excitation in line emission from CO (Umemoto et al. 1992), SiO (Mikami et al. 1992), and H_2 (Hodapp 1994). This is an ideal laboratory to study the chemical alterations induced by the shocks. For instance, ammonia (NH_3) and methanol (CH_3OH) are two molecules which were known to be abundant in interstellar ice mantles, and were thus expected to be desorbed from grains. Recent observations of L 1157 in lines of these two molecules have confirmed that both species have enhanced abundances in the regions shocked by the L 1157 outflow (Bachiller et al. 1993, 1995b). Methanol is enhanced by a factor of ~ 400 toward the blueshifted lobe of L 1157, whereas ammonia is enhanced by at least one order of magnitude. Measuring the abundance of CH_3OH is crucial, since this molecule is thought to dominate the chemical processes where it is abundant, as in the Orion compact ridge. The (3,3) line of NH_3 near λ 1.3 cm is particularly intense toward the L 1157 outflow lobes, and it becomes possible to image the flow with the VLA (which provides a resolution of $\sim 5''$ in its D configuration). Such VLA images reveal that the high-velocity ammonia arises from a series of bow shocks along the outflow axis (Tafalla & Bachiller 1995).

A description of the complex shock-chemistry found around bipolar outflows clearly requires high-resolution multiline observations of a number of different molecular species. Recent molecular line surveys of cold low-mass stars (NGC1333/IRAS4: Blake et al. 1995; IRAS16293: Blake et al. 1994, van Dishoeck et al. 1995) are proving to be very useful in examining the relative importance of different processes such as sputtering from the dust grains, depletion onto the mantles, and gas-phase reactions.

Finally, we stress that the detection of molecular lines from the shocked regions is interesting not only because of the chemical studies, but also because it opens the possibility of estimating the physical conditions of the gas. The case of ammonia is particularly interesting, since this is the best interstellar thermometer. In L 1157, the shocked gas is found to be heated to more than 60–80 K, i.e., at least a factor of 5 over the ambient quiescent gas. Furthermore, multiline studies of methanol can provide estimates of the gas volume density; in the L 1157 shocked region, Bachiller et al. (1995b) found densities in excess of $10^6 \mathrm{cm}^{-3}$.

References

André, P., Ward-Thompson, D., Barsony, M.: 1993, ApJ 406, 122
Bachiller, R.: 1996, Ann. Rev. Astron. Astrophys., in press
Bachiller, R., Gómez-González, J.: 1992, A & A Reviews 3, 257
Bachiller, R. et al.: 1990, A&A 231, 174

Bachiller, R., André, P., Cabrit, S.: 1991a, A&A 241, L43
Bachiller, R., Martín-Pintado, J., Fuente, A.: 1991b, A&A 243, L21
Bachiller, R., Martín-Pintado, J., Fuente, A.: 1993, ApJ 417, L45
Bachiller, R., Tafalla, M., Cernicharo, J.: 1994, ApJ 425, L93
Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., Martín-Pintado, J.: 1995a, A&A, 299, 857
Bachiller, R., Liechti, S., Walmsley, C.M., Colomer, F.: 1995b, A&A 295, L51
Bally, J., Lada, C.J.: 1983, ApJ 265, 824
Bally, J., Lada, C.J., Lane, A.P., 1993, ApJ 418, 322
Blake, G.A. et al.: 1994, ApJ 428, 680
Blake, G.A. et al.: 1995, ApJ 441, 689
Cantó, J., Raga, A.: 1991, ApJ 372, 646
Cernicharo, J., Reipurth, B.: 1996, in preparation
Cernicharo, J., Neri, R., Reipurth, B., Bachiller, R.: 1996, in preparation
Chernin, L.M.:1995, ApJ 440, L97
Chernin, L.M., Masson, C.R.: 1991, ApJ 382, L93
Chernin, L.M., Masson, C.R., Gouveia Dal Pino, E.M., Benz, W.: 1994a, ApJ 426, 204
Chernin, L.M., Masson, C.R., Fuller, G.: 1994b, ApJ 436, 741
Curiel, S., Raymond, J.C., Rodriguez, L.F., Cantó, J., Moran, J.M.: 1990, ApJ 365, L85
Davis, C.J. et al.: 1994, MNRAS 266, 933
Dutrey, A., Guilloteau, S., Bachiller, R.: 1996, in preparation
Dyson, J.E.: 1984, Astrophys. Space Sci. 106, 181
Edwards, S., Snell, R.L.: 1982, ApJ 261, 151
Edwards, S., Snell, R.L.: 1983, ApJ 270, 605
Edwards, S., Snell, R.L.: 1984, ApJ 281, 237
Gueth, F., Guilloteau, S., Bachiller, R.: 1996, A&A, in press
Guilloteau, S., Bachiller, R., Lucas, R., Fuente, A.: 1992, A&A 265, L49
Hartigan, P., Morse, J.A., Heathcote, S., Cecil, G.: 1993, ApJ 414, L121
Heathcote, S. et al.: 1996, in preparation
Hodapp, K.W.: 1994, ApJSS 94, 615
Kwan, J., Scoville, N.: 1976, ApJ 210, L39
Lada, C.J.: 1985, Ann.Rev.Astron.Astrophys. 23, 267
Lada, C.J., Fich, M.: 1996, ApJ, 459, 638
Martín-Pintado, J., Bachiller, R., Fuente, A.: 1992, A & A, 254, 315
Masson, C.R., Chernin, L.M.: 1993, ApJ 414, 230
McMullin, J.P., Mundy, L.G., Blake, G.A.: 1994, ApJ 437, 305
Mikami, H., Umemoto, T., Yamamoto, S., Saito, S.: 1992, ApJ 392, L87
Mundt, R., Brugel, E.W., Bührke, T.: 1987, ApJ 319, 275
Olberg, M., Reipurth, B., Booth, R.: 1992, A&A 259, 252
Raga, A.C.: 1991, AJ 101, 1472
Raga, A.C., Cantó, J., Binette, L., Calvet, N.: 1990, ApJ 364, 601
Raga, A.C., Cabrit, S.: 1993, A&A 278, 267
Raga, A.C. et al. 1993: A&A 276, 539
Reipurth, B.: 1989, Nature 340, 42
Reipurth, B., Olberg, M.: 1991, A&A 246, 535
Reipurth, B., Heathcote, S.: 1993, in *Astrophysical Jets*, Cambridge Univ. Press p.35
Richer, J.S., Hills, R., Padman, R.: 1992, MNRAS 254, 525
Snell, R.L., Loren, R.B., Plambeck, R.L.: 1980, ApJ 239, L17
Snell, R.L., Bally, J., Strom, S.E., Strom, K.M.: 1985, ApJ 290, 587
Stahler, S.W.: 1994, ApJ 422, 616
Tafalla, M., Bachiller, R.: 1995, ApJ 443, L37
Terebey, S.: 1991, Mem.S.A.It. 62, 823
Umemoto, T. et al.: 1992, ApJ 392, L83
van Dishoeck, E.F., Blake, G.A., Jansen, D.J., Groesbeck, T.D.: 1995, ApJ, 447, 760
Zuckerman, B., Kuiper, T.B.H., Kuiper, E.N.R.: 1976, ApJ 209, L137