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The jet-outflow connection: new results from ALMA

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Abstract. The connection between the highly collimated jets and the molecular outflows commonly seen toward the youngest stellar objects remains a major challenge. Over the years, a number of models have been proposed to unify these two phenomena, either in terms of jets only or by assuming the presence of an invisible wide-angle wind that surrounds the jet. Observations have so far provided little constraints on these models due to a combination of selection effects and limited sensitivity, but new data coming from the ALMA interferometer promise to change this situation. Here I summarize the results from two ALMA projects aimed to better understand the connection between jets and outflows, and to hopefully shed new light on the still mysterious agent that powers these two energetic phenomena.

Key words. Stars: formation – ISM: jets and outflows – ISM: molecules – Radio lines: ISM

1. Introduction

Jets and outflows are some of the best-known and most spectacular signatures of the star-formation process. They illustrate the unexpected violence of stellar birth, and reveal that in addition to gravitational collapse, the formation of a star requires the ejection of significant amounts of material at hypersonic speeds. Jets and outflows likely have a significant impact on the parental cloud, as evidence by numerous tracers of shocked gas, and may even regulate the star-formation process by injecting stabilizing turbulent motions on the surrounding gas (see Frank et al. 2014 for a recent review).

In their chapter 13, Stahler & Palla (2005) present a very readable and complete review of jets and outflows, which starts with the humble acknowledgement that they "were wholly unanticipated by theorists, who are still struggling to understand the basic mechanisms of wind generation and jet propagation." My first contact with Francesco dates back to the time when him and Steve were working on their book, and I was a graduate student at Berkeley. The fact that two eminent astronomers would come to consult with a graduate student about such important matters made an impression on me, although it is obvious that I was not of much help clarifying the "outflow problem." Almost two decades later, and after an often frustrating observational effort to understand outflows, I feel that we may be getting close to finally tackling this problem, partly thanks to the enhanced sensitivity and resolution provided by ALMA. In this talk, I present the results from two recent ALMA observations of jets and outflows that seem to shed new light on some of the old outflow questions addressed by Francesco and Steve in their already-mentioned chapter 13. I want to think that Francesco would have liked these results, and I hope that Steve agrees.

2. Outflows with molecular jets

Jets and outflows are undoubtedly part of the same mass ejection phenomenon that is powered by a newly formed star. Most of the time, however, they are studied independently due to their very different observational signatures. Jets are mostly observed at optical wavelengths due to their relatively high excitation (e.g., Reipurth & Bally 2001), while outflows tend to be observed at mm wavelengths due to their lower excitation and molecular composition (e.g., Bachiller & Tafalla 1999). Since optical observations require low extinction and mm-wave observations are only possible if enough gas (and dust) is present, observations of jets and outflows are often mutually exclusive, and only a small number of targets have been the subject of combined jet and outflow observations (e.g., Chernin & Masson 1995). As a result, the relation between the jets and the outflows has remained poorly understood, and this has had important consequences on our understanding of the intrinsic geometry of the protostellar wind.

In general terms, two families of models have been proposed to explain the geometry of the protostellar wind. The so-called jet-driven models assume that jets are the sole responsible agents for accelerating the ambient material in outflows. Since jets are narrow and supersonic, the main challenge of these models is to broaden the effect of the jets so that they can set in motion the much wider distribution of accelerated material seen by molecular observations. Different mechanisms have been proposed for this, including jet wandering or precession (Masson & Chernin 1993), entrainment (Stahler 1994), and internal shocks (Raga et al. 1993).

The alternative to the jet driven models is represented by the the so-called wide-angle winds, which propose that a less collimated wind component surrounds the jet and accelerates the molecular outflow. In the so-called unified model of Shang et al. (2006), the jet is not an independent component, but merely the central part of a wide-angle wind whose density decreases rapidly away from the axis.

A promising approach to explore the relation between jets and outflows, and thus constrain the geometry of the protostellar wind, is to focus on a small group of systems that have, in addition to the usual wide molecular outflow, a highly collimated molecular jet. These systems seem to correspond to the youngest protostars, and to represent the only targets where both outflow and jet components can be observed simultaneously with a single tracer. In this paper, I present the first results of a dedicated effort to study with ALMA two members of this selected group: IRAS 04166 and L1448.

3. ALMA observations of IRAS 04166+2706

IRAS 04166+2706 (IRAS 04166 for short) is a Class 0 object that powers the only outflow with a molecular jet known to exist in the Taurus star-forming cloud. Its jet component was originally identified from the presence of discrete extremely high-velocity (EHV) features in the CO spectra (Tafalla et al. 2004) that are similar to those found in the L1448 molecular jet (Bachiller et al. 1990). Further IRAM PdBI observations by Santiago-García et al. (2009), and illustrated in Fig. 1, resolved the emission from IRAS 04166 in its two main components: a pair of conical shells at low velocities and a highly collimated and fragmented jet in the EHV regime.

In addition to revealing the overall outflow geometry of IRAS 04166, the PdBI observations of Santiago-García et al. (2009), and additional SMA observations by Wang et al. (2014), identified a series of velocity oscillations in the EHV emission. These oscillations appear in position-velocity diagrams along the jet as a systematic saw-tooth pattern, and have been interpreted as resulting from the lateral ejection of gas in internal jet shocks.

Unfortunately, the limited sensitivity of the PdBI and SMA observations precluded determining the 2D distribution of the gas responsible for the saw-tooth pattern in the position-velocity diagrams. To overcome this

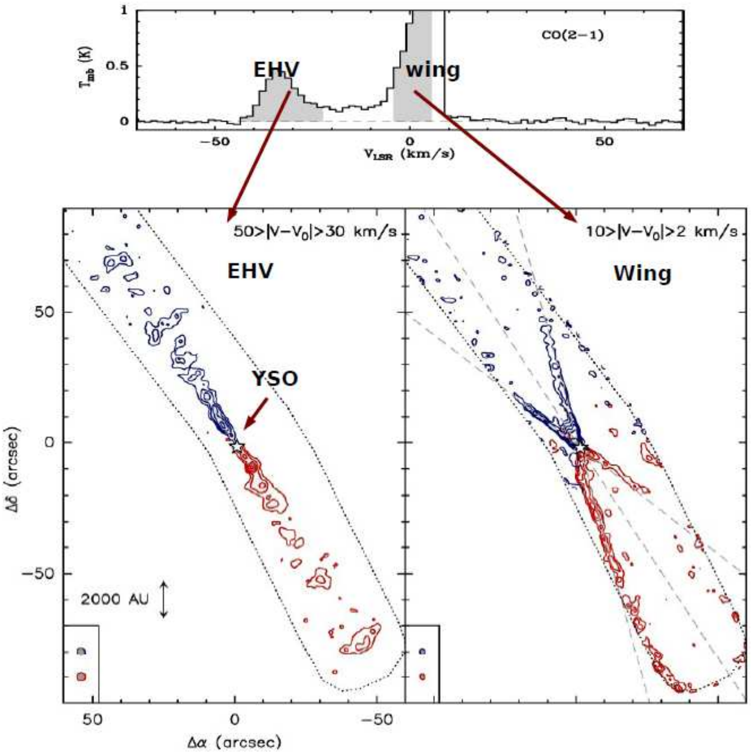

Fig. 1. Main properties of the IRAS 04166 outflow. Top: averaged CO(2–1) spectrum over the blue lobe indicating its two distinct features: a low-velocity wing and a discrete extremely high velocity (EHV) component. Bottom: spatial distribution of the two velocity components. The low-velocity wing corresponds to a pair of conical shells that emerge from IRAS 04166. The EHV gas consists of a pair of highly collimated and fragmented jets. Data from Santiago-García et al. (2009) obtained with the IRAM PdBI.

limitation, we carried out ALMA observations of two jet positions with concentrated emission and located symmetrically with respect to IRAS 04166. These positions are indicated with circles in the left panel of Fig. 2, and were observed in an ALMA compact configuration using CO(2–1) and SiO(5–4). A full report on this work has been recently presented in Tafalla et al. (2017).

The ALMA maps, especially those of the brighter CO(2–1) line, show that the EHV emission from IRAS 04166 behaves in a simple and systematic way. In both ALMA fields, the EHV CO(2–1) emission traces an elliptical region whose major axis is perpendicular to the jet direction. The velocity of the emission, in the reference frame of the jet, systematically changes from blue to red along the minor axis, as illustrated in the central panel of Fig. 2, which shows the first moment maps of the CO(2–1) emission. As can be seen, the emission gradually changes by about 20 km s^{-1} from blue-shifted toward the south-west to red-shifted toward the north-east.

This systematic change in the centroid velocity of the emission, together with the elliptical distribution, suggests that in each ALMA field the CO-emitting gas is located in a disk-like structure that is expanding radially away from its axis. This type of distribution is illustrated in the right panel of Fig. 2, and is the basis of the geometrical model used in Tafalla et al. (2017) to reproduce the main emission features. As shown in the figure, to properly repro-

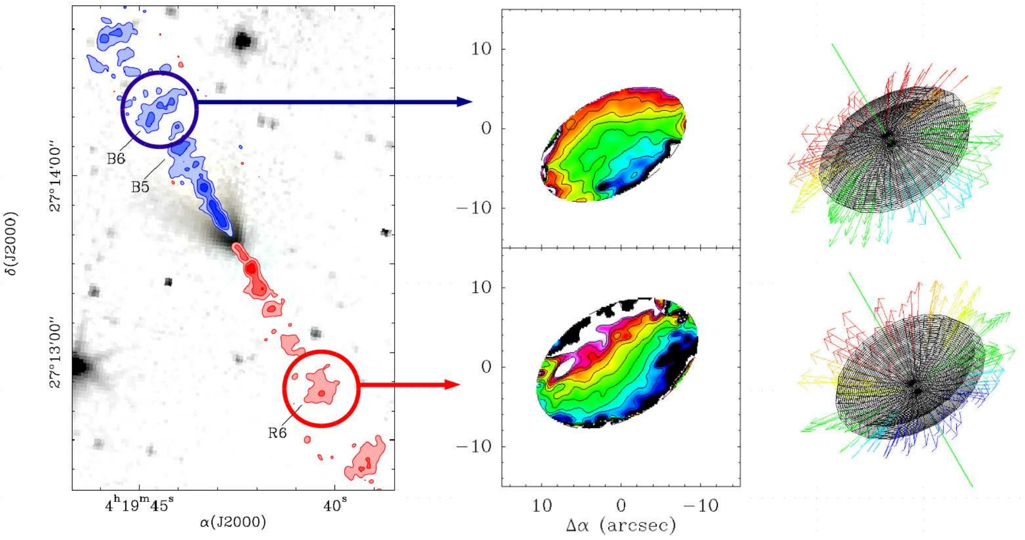

Fig. 2. Summary of the ALMA observations of the IRAS 04166 outflow. Left: IRAM PdBI map showing with circles the two regions observed with ALMA. Middle: first moment maps of the CO(2–1) emission. Note the systematic pattern of blue-shifted emission toward the south-west and red-shifted emission toward the north-east. Right: schematic view of the model used to reproduce the observed emission, which consists of a pair of expanding bow-shocks resulting from internal shocks inside the jet.

duce the pattern seen in the velocity centroid maps, each disk-like structure has to curve away from the protostar, in the same manner expected for a bow shock that moves away from the central source.

The above geometrical modeling of the CO(2–1) ALMA emission not only confirms the original interpretation that the EHV gas represents material ejected laterally in internal jet shocks, but provides a quantitative description of the emitting gas and its velocity field. With this description, it is possible to calculate the amount of linear momentum ejected sideways, and to compare this amount with what is needed to open up the outflow cavity and accelerate the slower molecular outflow. The result depends on the number of ejections that have occurred over the lifetime of the outflow, which unfortunately is uncertain, but it can be approximated from the length of the outflow lobes and the time separation between ejections. As shown in Tafalla et al. (2017), such an estimate suggests that a sequence of lateral ejections could indeed have accelerated the rest of the outflow seen an low velocities. If this result is confirmed by observations of other molecular jets, it is possible that models of pulsating jets like those presented by Raga et al. (1993) could explain the acceleration of molecular outflows.

4. ALMA observations of L1448

The second outflow with a molecular jet observed with ALMA is L1448 in the Perseus star-forming cloud. L1448 was the first outflow where an EHV component was identified (Bachiller et al. 1990), and although it is slightly more distant than IRAS 04166, it is significantly brighter in its molecular emission. The mapping strategy for L1448 was complementary to that for IRAS 04166, since we mapped the innermost part of the outflow using two overlapping positions around the central protostar. As with IRAS 04166, we observed together the CO(2–1) and SiO(5–4) lines, which represent the best tracers of the EHV regime. The L1448 data were obtained only a few months ago, so their analysis is still

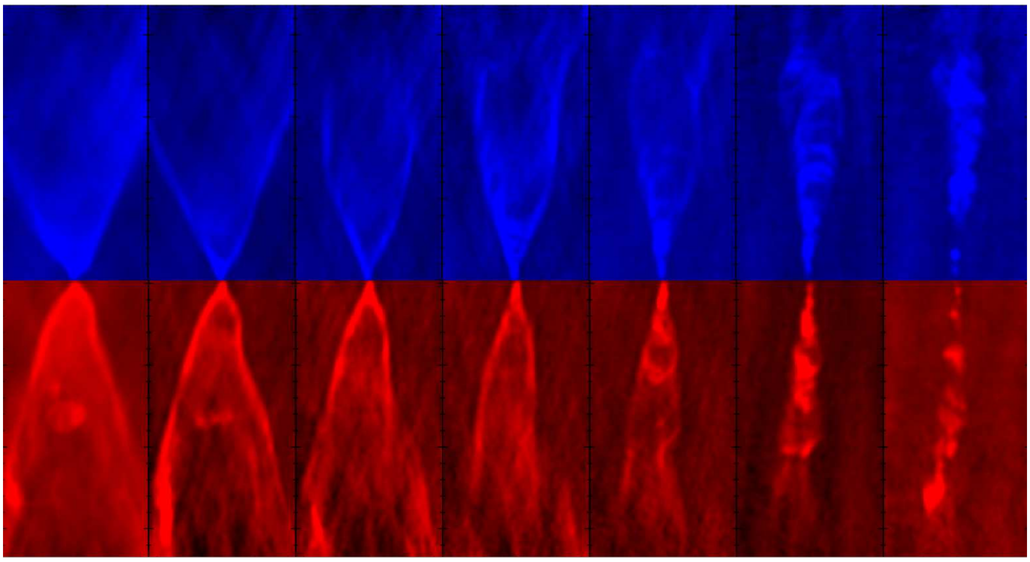

Fig. 3. Channel maps of the CO(2–1) emission from the L1448 outflow observed with ALMA. Each map corresponds to a 10 km s^{-1} interval ranging from the ambient cloud regime (left panels) to the EHV regime (rightmost panels). For easier comparison, the maps have been rotated.

in progress and the interpretation preliminary. Still, the features of the emission seem clear enough from the maps that the main elements of the interpretation are unlikely to change under further modeling. These features are summarized in Fig. 3 with a series of CO(2–1) channel maps each covering a 10 km s^{-1} velocity interval (for easier presentation, the outflow has been rotated to match the vertical axis). As can be seen, in both outflow lobes, the EHV emission (rightmost panels) appears jet like, but quickly evolves into a shell geometry whose opening angle gradually increases as the velocity of the outflow decreases. This systematic transition between the jet and the shell regimes strongly suggest a physical connection between the two, and the arclike structures seen in the EHV gas, resembling those seen in IRAS 04166, point to lateral expanding motions away from the jet axis. Again, a model of lateral expanding motions due to a pulsating jet seems therefore to reproduce well the observations obtained with the ALMA interferometer.

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