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Molecular outflows in young stellar objects

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Abstract. Of kinematical features related to star formation, molecular outflows are to date the only phenomena known to be ubiquitous in both low- and high-mass star-forming regions. With pc-sized extensions, molecular outflows can be resolved with present-day telescopes, and can provide key information about the forming mechanism of the central star. We give a brief review of observational properties of low-mass molecular outflows, and present showcases of massive molecular outflows.

Key words. Stars: formation – Stars: early types – ISM: jets and outflows

1. Introduction

Young stars and protostars produce powerful bipolar outflows which are observable over a wide range of wavelengths, from the ultraviolet to the radio. They appear as the most magnificent manifestation in the earliest stages of star formation and are a common phenomenon in young stellar objects of all the masses. Since outflows take place on parsec scales, they are often the first clear sign that reveals the formation of a new star. Moreover, for distant objects, and therefore in particular for high-mass young stellar objects (see Sect. 3), they are far easier to resolve spatially than other processes taking place in the inner region close to the protostar(s). Thus they offer an alternative approach to study the formation mechanism of massive stars.

2. Low-mass molecular outflows

Leading models of low-mass outflows provide the most complete and detailed pictures about how a Sun-like star forms: outflows are powered by disk accretion, which launches a magneto-centrifugally collimated wind, either an X-wind (Shu et al. 1994, 2000) or a disk-wind (Pudritz & Norman 1983; Pudritz et al. 2007); the wind carries out angular momentum and energy into the parent molecular cloud and local ISM, sweeping up the ambient gas into a molecular outflow, which is typically seen in rotational transitions of CO (see reviews of Bachiller 1996; Arce et al. 2007). Table 1 lists key parameters of low-mass molecular outflows derived from CO observations. Morphologically, collimated jet-like outflows and well-shaped bi-conical outflows are often seen in low-mass protostars. Arce & Sargent (2006) show that low-mass outflows continue to widen from jet-like structures to wide-angle shells as the central objects evolve from class 0 to class II stages; such a picture can be reproduced by simulations of the MHD wind models (Shang et al. 2006; Fendt 2009).

Best objects to investigate the morphology and kinematics of the jet launching zone are classical T Tauri stars, which, being rela-

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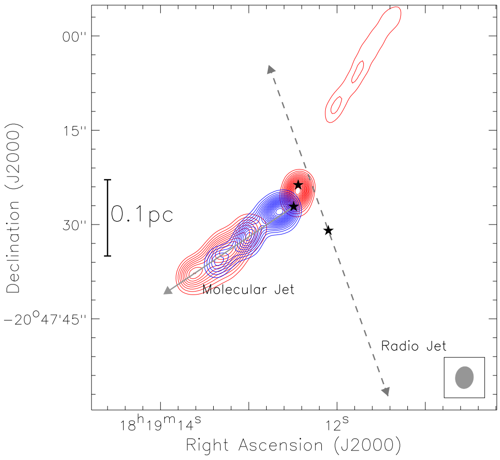

Fig. 1. The velocity integrated map of the CO (2–1) emission in HH 80-81. Blue and red contours show emission integrated from −95 to −20 km s^{-1} and from 20 to 95 km s^{-1} relative to the systemic velocity, respectively; three stars denote three star-forming cores; a solid arrow marks a molecular jet discussed in the text, and dashed arrows mark a nearby radio jet; a filled ellipse in the lower right shows the synthesized beam of the observation, and a bar in the left shows a linear scale of 0.1 pc.

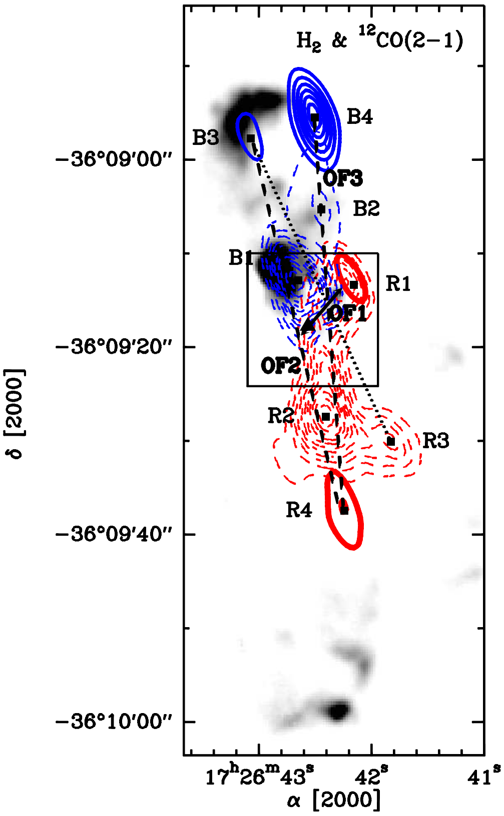

Fig. 2. Integrated emission of the blue- and red-shifted wings in the CO(2–1) line overlaid on the H_2 emission (grey scale) towards the massive star-forming region IRAS 17233–3606. The solid contours show the EHV blue- (v=[-200,-130] km s^{-1}) and red-shifted emission (v=[90,120] km s^{-1}); the dashed contours mark the HV blue- (v=[-130,-25] km s^{-1}) and red-shifted emission (v=[16,50] km s^{-1}).

tively evolved, are not anymore embedded in the parental cloud (and can therefore be observed in the optical with high spatial resolution) and still have jets. Observations show that T Tauri jets have morphologies dominated by emission knots, that strongly resemble the HH jets emanating from younger (class 0/I) sources. Moreover (McGroarty & Ray 2004) found that they can also extend for several parsecs as is the case with outflows from more embedded YSOs. Thus the observations clearly suggest that the same ejection mechanism is at work at all phases of star formation.

3. Massive molecular outflows

Since 1990s, single-dish surveys have shown the common presence of molecular outflows in high-mass ($> 8M_\odot$) star-forming regions(Shepherd & Churchwell 1996; Zhang et al. 2001; Beuther et al. 2002). These outflows have masses typically at orders of 1–100 $M_\odot$, while their velocities and size scales are comparable to low-mass outflows. As massive stars form in regions far away (typically a few kpc) from us and in a clustered mode, most single-dish observations cannot resolve the morphology and kinematics of massive outflows or identify their driving sources. Many basic properties of massive molecular outflows, e.g., their driving mechanism and evolutionary scenario, remain unclear. Here we present case studies of massive outflows making use of high-angular-resolution interferometric observations.

Table 1. Parameters of low-masses outflows

Outflow Parameters	Characteristic Values
Size	0.1-1 pc
Mass	0.01-1 $M_\odot$
Velocity	10-100 km s^{-1}
Momentum	0.1-10 $M_\odot$ km s^{-1}
Mass loss rate	< 10^{-5} $M_\odot$ yr^{-1}
Momentum loss rate	10^{-6}-10^{-4} $M_\odot$kms^{-1} yr^{-1}

Figure 1 shows well-collimated outflows seen in a 20,000 $L_\odot$ star-forming region HH 80-81(Qiu & Zhang 2009). A remarkable molecular "jets" is found toward a warm (30–40 K), massive ($> 10M_\odot$) star-forming core near to a pc-scale radio jet. The molecular jet exhibits extremely-high-velocity emission reaching 100 km s^{-1} in both blue and red lobes, suggesting radial velocities of hundreds of km s^{-1}. The mass and momentum loss rates of the jet amount to orders of 10^{-4} $M_\odot$ yr^{-1} and 10^{-3}–10^{-2} $M_\odot$ km s^{-1} yr^{-1}, respectively. In particular, the jet consists of compact and fast moving entities, known as "molecular bullets" first seen in low-mass outflows. The discovery of this molecular jet manifests a disk-mediated, episodic accretion for the formation of the central high-mass star.

Figure 2 shows another example of collimated molecular outflows from massive YSOs. In this case, at least three molecular flows are detected in the star-forming region IRAS 17233–3606 (Leurini et al. 2009), one of which associated with extremely high velocities ($|v - v_{\rm LSR}| > 120$ km s^{-1})). All molecular outflows have a counterpart in H_2. IRAS 17233–3606 represents a typical example of the multiplicity of outflows in massive star-forming regions and of their complexity.

4. Summary

There has been accumulating evidence from interferometric studies that massive molecular outflows are morphologically and kinematically similar to low-mass outflows. This supports the hypothesis that massive stars form in an essentially similar way as the formation of low-mass stars. However, it is unknown whether the low-mass outflows models, e.g., the X-wind model or disk-wind model, can be scaled to massive outflows; so far there is no well-developed theoretical model for massive outflows. The statistics of high-resolution, high-fidelity observations of massive outflows needs to be improved. In particular, the well-known Orion-KL outflow stands alone with an explosive morphology (Zapata et al. 2009), which is likely completely different from classical bipolar outflows.

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