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Letter to the Editor

Discovery of a molecular outflow, near-infrared jet and HH objects towards IRAS 06047–1117

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Abstract. We report discovery of a new young stellar object driving a point-symmetric, near-infrared jet and molecular outflow. The YSO is associated with IRAS 06047−1117 and is embedded in a dense molecular cloud core located southeast of Orion A. The jet is seen in the H_2 $v = 1{-}0$ line at 2.12 μm and extends over a total length of about ∼0.4 pc. The driving source is optically invisible and has near-infrared colors and a spectral energy distribution consistent with a Class I source with an estimated luminosity of 6 $L_\odot$. Two Herbig-Haro objects are seen in Hα images located close to the positions of maximum H_2 emission.

Key words. infrared: stars – ISM: clouds – ISM: individual (IRAS 06047–1117) – ISM: jets and outflows – stars: formation – stars: mass-loss

1. Introduction

Mass ejection from young stars constitutes one of the major signposts of star formation in a molecular cloud. The ejection of mass may be detected in the form of high-velocity winds, jets, and molecular outflows (e.g. Königl & Pudritz 2000; Eisloffel et al. 2000; Richer et al. 2000) occurring simultaneously with the accretion of material from the surroundings of the star. The flow of gas ejected from the vicinity of the forming star results in the entrainment of ambient gas which may develop shocks, or Herbig-Haro objects seen as nebular emission rich in spectral lines (e.g. Hartigan et al. 2000), both at optical (e.g. Hα emission) and near-infrared (e.g. $v = 1 - 0$ S(1) H_2) wavelengths.

The very youngest jets are associated with the youngest stars (protostars). Because these stars and jets are deeply embedded in the parental cloud, they are quite often only detectable at near-infrared wavelengths (e.g. McCaughrean et al. 1994; Davis et al. 1995; Moreira & Yun 1995; Yun et al. 1997; Zinnecker et al. 1998). In several cases, observed protostellar jets appear to exhibit wiggling (e.g. Mundt 1998; Davis et al. 1997), some degree of bending (e.g. Eislöffel & Mundt 1997), including the presence of misaligned jet components (e.g. Eislöffel 2000). In other cases, the emission seen does not trace the jet itself but rather the interaction of the jet with the surrounding ambient medium (e.g. McCaughrean et al. 1994; Yun 1997).

As part of an effort to produce a catalog of protostars and young stellar objects (YSOs) identified in the IRAS data base, we have been studying IRAS 06047–1117, a PSC source located southeast of Orion A. In their optical and near-infrared survey of transitional YSOs, Magnier et al. (1999) listed this source as a very red star with possible emission nebulosity. In this paper, we report discovery of a molecular outflow (seen in millimetre line maps), of an H_2 jet (seen in near-infrared images), and of HH objects (seen in Hα images) from IRAS 06047–1117.

2. Observations

Millimetre observations were carried out using the Swedish-ESO Submillimetre Telescope (SEST) in Chile during 1999 September and the FCRAO telescope in Massachusetts, USA during 2000 April. At SEST, a set of 9 CO ($J = 1{-}0$) spectra and one HCN ($J = 1{-}0$) spectrum were obtained towards IRAS 06047–1117. We used SIS receivers and the 2000-channel acousto-optical spectrometer as a back-end, with a resolution of about

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0.2 km s^{-1}. At FCRAO, observations of CO ($J = 1$–0) took place using the 16-pixel SEQUOIA receiver which fed an autocorrelator with 512 channels, resulting in spectra with 0.2 km s^{-1} channels.

Near-infrared (JHK) observations were conducted during 2000 March using the 1 m YALO[1] telescope, at the Cerro Tololo Inter-American Observatory in Chile, equipped with the ANDICAM camera. The ANDICAM near-infrared array contains 1024 × 1024 pixels, and was used at a plate scale of 0.21 arcsec/pixel.

Additional near-infrared images of IRAS 06047–1117 were obtained on 2000 October 18 with the Omega Prime near-IR camera (Bizenberger et al. 1998) on the Calar Alto 3.5 m telescope. The pixel scale of Omega Prime is 0.396″ per pixel, the seeing was typically ∼1.4″. Images were taken through the NB2122 filter, a 1% filter centered on the $v = 1 - 0$ S(1) line of the H_2 molecule at 2.12 μm, and through a broad-band K' filter ($1.944 - 2.292$ μm). At each of 6 different dither positions series of 10 images with 30 s exposure time in the NB2122 filter and 2 s exposure time in the K' filter were taken. The total net integration time is therefore 30 min in the NB2122 filter and 2 min in the K' filter. Similar H_2 line observations were also obtained using SOFI on the ESO NTT on 2000 October 11.

In addition, an Hα CCD image was obtained at the 1.5 m meter telescope of the Observatory of Sierra Nevada, near Granada, Spain. The CCD camera has 1024 × 1024 pixels and was used at a image scale of 0.32 arcsec/pixel. The exposure time used was 1200 s.

3. Results

3.1. Molecular outflow and distance

In Fig. 1, we present the SEST CO ($J = 1$–0) spectra (top panel) and the HCN ($J = 1$–0) spectrum (bottom panel) obtained towards IRAS 06047−1117. The CO spectra show clear evidence for a molecular outflow with wings extending to about 10 km s^{-1} away from the line center velocity. The northwest spectra exhibit "blue" wings while the spectra toward southeast exhibit "red" wings. Interestingly, there is an almost perfect point-symmetry relative to the position of IRAS 06047−1117 located at the centre. The HCN line is relatively strong (integrated line intensity of 1.4 K km s^{-1}, e.g. Afonso et al. 1998), confirming the association with a dense molecular core. This core is clearly seen in absorption in the Digitized Sky Survey southeast of the Orion A molecular cloud. The molecular gas displays a LSR velocity of 6.0 km s^{-1}. This low value of the radial velocity indicates that the source is likely to be nearby. Based on the value of the radial velocity and on the lack of foreground stars seen on optical images, we estimate a distance of about 500 pc to the source. Given this value, very close to the Orion distance of 450 pc, it is likely that the source is part of the Orion molecular complex.

[1] YALO is the **Y**ale-**A**URA-**L**isbon-**O**hio consortium (Bailyn et al. 1999).

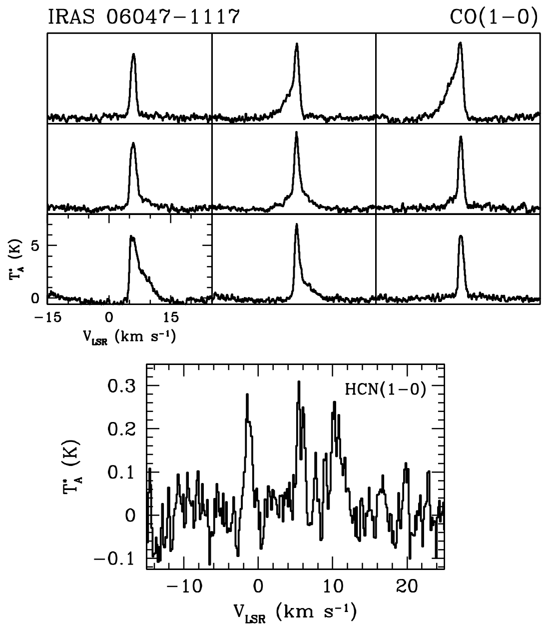

Fig. 1. (*top*) CO ($J = 1$–0) spectra towards IRAS 06047−1117. The spectra are presented in their relative angular positions on the sky, in a grid of 46 arcsec step size. Notice the strong point-symmetry relative to the central position (location of the IRAS source). (*bottom*) HCN(1−0) spectrum towards IRAS 06047−1117. The molecular gas displays a LSR velocity of about 6 km s^{-1}.

Figure 2 presents the FCRAO CO ($J = 1$–0) map of velocity-integrated intensity towards IRAS 06047−1117. The two lobes, blue (solid line) and red (dashed line), are strong and show very little overlap. The outflow appears well collimated, roughly oriented in a southeast-northwest direction (position angle, PA $\sim -46 \pm 9°$, of the line connecting the peaks of the two lobes). At 500 pc, the peak-to-peak length of the outflow is about 0.4 pc, similar to the average length of low-mass stellar outflows.

3.2. Near-infrared jet and HH object

Figure 3a presents the Calar Alto 2.12 μm $v = 1 - 0$ S(1) molecular hydrogen image towards IRAS 06047–1117. The image covers 4 × 4 $arcmin^2$ centered at the position of IRAS 06047–1117. A bright point source is seen near the center of the image (IRS). This source (whose J2000 coordinates are $\alpha = 06^h07^m08^s.5$, $\delta = -11°17'51''$) is optically invisible (not present in the Digital Sky Survey images). Photometry of this source made on our YALO JHK images yielded magnitudes of $J = 16.8$, $H = 13.2$, and $K = 10.6$. The values of the $(H - K)$ and $(J - H)$ colours place this source in the region of the near-infrared $(H - K)$, $(J - H)$ colour-colour diagram occupied by Class I YSOs (Lada & Adams 1992). This is compatible with the spectral energy distribution obtained from JHK and IRAS fluxes. This good agreement in YSO classification together with the good positional coincidence of IRS with IRAS 06047–1117 indicate that IRS is the

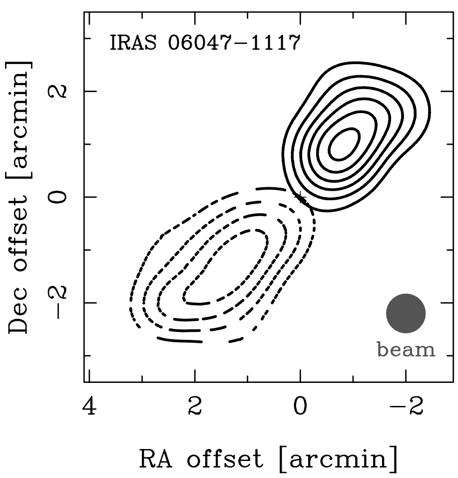

Fig. 2. FCRAO CO ($J = 1{-}0$) map of velocity-integrated intensity towards IRAS 06047−1117. The outflow appears well collimated, roughly oriented in a southeast-northwest direction. A cross marks the position of the IRAS source. The blue and red lobes cover velocities, respectively, between −7 and 4 km s^{-1} and between 8 and 17.5 km s^{-1}. The first contour level is at 3 K km s^{-1}. Subsequent contours are stepped by 1.5 K km s^{-1}.

near-infrared counterpart of IRAS 06047–1117 and that it is a Class I YSO. Using the values of the *IRAS* fluxes for IRAS 06047–1117 together with the above near-infrared magnitudes, we estimate the bolometric luminosity of IRS to be about 6 $L_\odot$ for a distance of 500 pc.

Analysis of the H_2 image reveals a curved jet-like structure traced in the light of the shock-excited molecular hydrogen emission, with peak intensities in the southeast and northwest, roughly coincident with the peaks of the molecular outflow. This is more clearly seen in Fig. 3b which presents the continuum subtracted H_2 image. This image was made by scaling the Calar Alto K' image appropriately so that when it was subtracted from the H_2 image, continuum sources (e.g. field stars) disappeared. The position of IRS is marked with a cross.

Interestingly, the jet emission located northwest of the IRS source (corresponding to the outflow blue lobe) delineates an arc that is very point-symmetric when compared to the jet emission seen toward the southeast (red lobe of the outflow). Thus, both the molecular outflow and the jet exhibit a strong point-symmetry relative to IRS. Furthermore, the line connecting the two peaks has the same general orientation as that of the molecular outflow (roughly southeast to northwest, PA $\sim -62 \pm 5°$) and extends across approximately 2.5 arcmin (or 0.4 pc, for the estimated distance of 500 pc).

Figure 4 shows the Hα image obtained towards IRAS 06047–1117. Notice the presence of nebular emission close to the locations of the brightest H_2 emission (Fig. 3). This identifies new Herbig-Haro objects associated with this star-forming region. These objects appear as faint nebular emission in the Digitized Sky Survey.

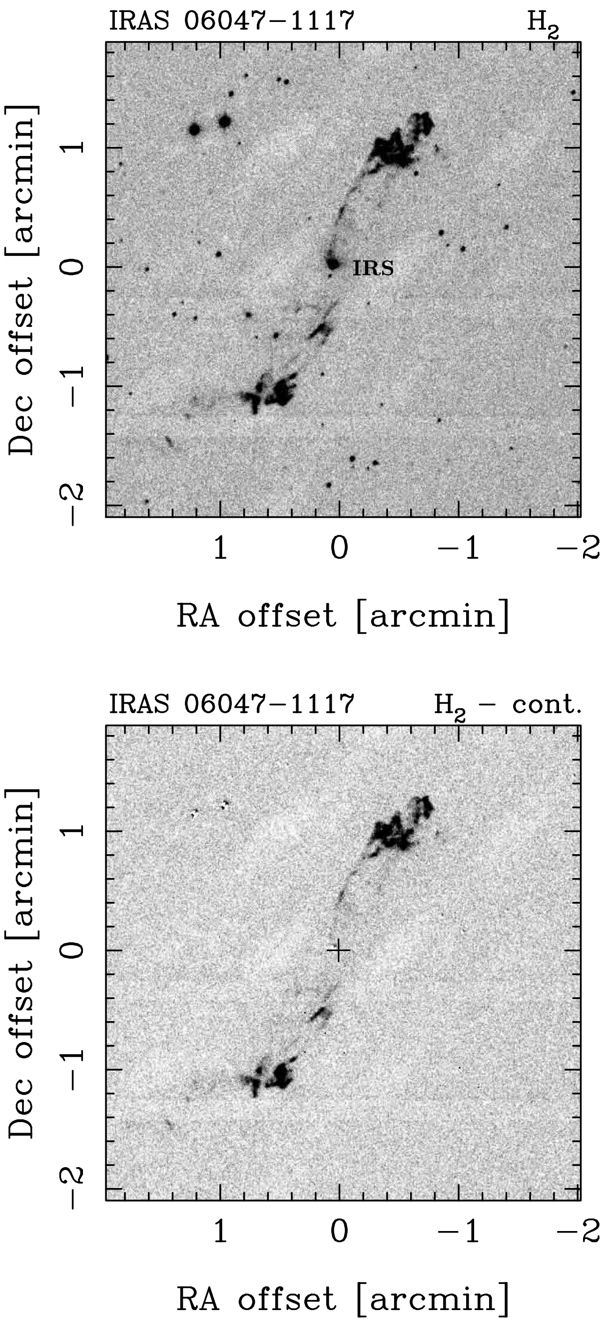

Fig. 3. a) (*top*) H_2 $v = 1-0$ S(1) image towards IRAS 06047–1117. The bright point source (IRS) seen near the center of the images is located 2″ away from IRAS 06047–1117. **b)** (*bottom*) Continuum subtracted H_2 image towards IRAS 06047–1117. A cross marks the position of the IRS source.

4. Discussion

The brightest parts of the H_2 emission appear to exhibit a peculiar S-shaped morphology. If we assume that the H_2 traces the underlying jet itself, then the jet would have a curved, S-shaped, point-symmetric morphology. Possible explanations for this might include the action of Lorentz forces between the jet and an external interstellar magnetic field (Fendt & Zinnecker 1998), a precessing jet (e.g. Dutrey et al. 1997), or the orbital motion of the driving

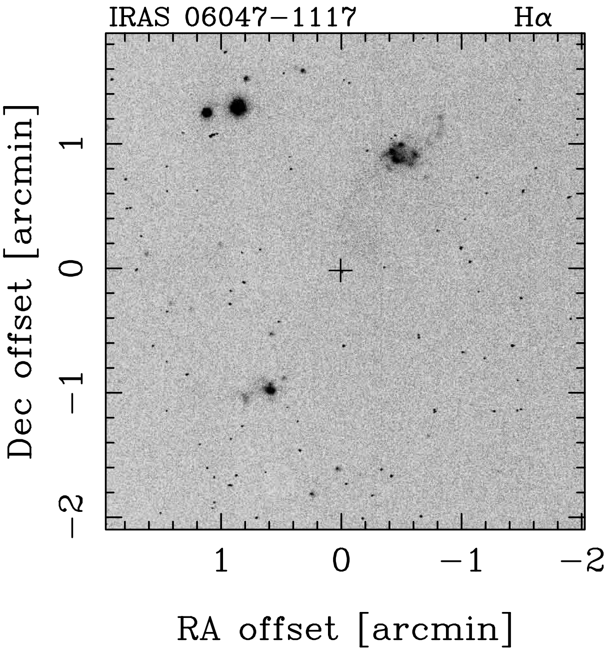

Fig. 4. Hα image towards IRAS 06047–1117. Notice the features located near the positions of the strongest H_2 emission (Fig. 3 bottom). These are Herbig-Haro objects. The two stars in the top left corner are unrelated field stars.

source in a binary system (Fendt & Zinnecker 1998). The mismatch between the position angles of the axes of the jet and the molecular outflow might be explained by this scenario.

However, Fig. 3b and our ∼1 arcsec seeing NTT images show evidence for faint emission associated with both sides of the flow, apparently filling out broader elliptical structures. This would tend to indicate that the actual jet is in fact invisible at these wavelengths, and that the H_2 emission is tracing out the edges of a cavity, where the jet interacts with the ambient medium (cf. HH211: McCaughrean et al. 1994; Gueth & Guilloteau 1999).

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