Discovery of new embedded Herbig-Haro objects in the $\rho$ Ophiuchi dark cloud

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Abstract. We report here the discovery of a $30''$-chain of embedded Herbig-Haro (HH) objects in the $\rho$ Ophiuchi dark cloud. These HH objects were first detected during a deep $K_S$-band observation (completeness magnitude for point source $\sim 19$) made with NTT/SOFI. We confirm their nature with follow-up observations made with $H_2 v=1–0$ S(1) narrow-band filter. We argue that they belong to two different jets emanating from two Class I protostars: the main component of the recently resolved subarcsecond radio binary YL W15 (also called IRS43), and IRS54. We propose also to identify the [S II] knot HH224NW 1 (Gómez et al. 1998) as emanating from a counterjet of YL W15. The alignment between these HH objects and the thermal jet candidate found in YLW15 by Girart et al. (2000) implies that this jet is not precessing at least on timescale $\sim (2–4) \times 10^4$ yr.

Key words. Open clusters and association: $\rho$ Ophiuchi dark cloud – infrared: stars – infrared: ISM – Stars: pre-main sequence – Herbig-Haro objects – ISM: jets and outflows

1. Introduction

In the 1950’s, objective prism surveys of dark clouds revealed optical small nebulae, associated with young stars, showing emission line spectra with very weak continua. Today, these Herbig-Haro (HH) objects are interpreted as shocks produced by the interaction of outflows from Young Stellar Objects (YSOs) and the interstellar medium (see review by Reipurth & Raga 1999).

The $\rho$ Ophiuchi dark cloud is one of the nearest (d$\sim$140 pc) active site of low-mass star formation, displaying a rich embedded cluster of $\sim$200 YSOs (see the updated census by the ISOCAM survey; Bontemps et al. 2001). It is thus one of the most suitable locations for the search of HH objects. Optical emission-line surveys (H$\alpha$, [S II]) have led to the detection of only 10 bona fide HH objects (Reipurth & Graham 1988; Wilking et al. 1997; Gómez et al. 1998; Reipurth 1999). As outlined by Wilking et al. and Gómez et al., most of these HH objects are located at the periphery of the cloud, in the lowest extinction area: optical surveys do not have access to embedded HH objects. Wilking et al. (1997) noted for all these nebulae a relatively high [S II]/H$\alpha$ ratio, which is a tracer of low excitation conditions, and thus indicates that $H_2$ is not destroyed after the bow shock; they suggested to use the shocked-$H_2$ transition at $\lambda=2.121$ $\mu$m to probe deeply embedded HH objects. Up to now in the $\rho$ Ophiuchi dark cloud, shocked-$H_2$ imaging was only performed to study molecular shocks in the CO outflow of the Class 0 protostar prototype VLA1623 (e.g., Davis & Eisloeffel 1995), which led to the detection of several $H_2$-knots; one of them was later detected in [S II] (HH313; Gómez et al. 1998).

We report here deep near-IR observations of the $\rho$ Ophiuchi dark cloud unveiling bow-shape structures and knots, and complementary observation with narrow-band filter confirming their nature as $H_2$ shocks. As these objects are not optically visible, we called them embedded HH objects, and discuss the possible exciting sources.

2. Observations and results

During the period April 4–7 2001, deep $J, H, K_S$-band observations of the $\rho$ Ophiuchi dark cloud were made by N.G. with NTT/SOFI, as follow-up of Chandra and XMM-Newton X-ray observations. The complete report of this follow-up, consisting of 5 pointings, will be published in an upcoming paper (Grosso et al., in preparation). We will focus here only on the pointing related to the detection of
new embedded HH objects, and located SE of the milli-
meter dense core Oph-B2 (Motte et al. 1998; see Fig. 1). This area was already surveyed by optical emission-line
surveys, but no HH objects were found.

We used the auto jitter imaging mode to obtain a total
integration time of 40 mn, with 6 s detector integration
time (DIT) and 1 mm-exposure frames. The near-IR standard
AS29-1 (Hunt et al. 1998) was observed several times
during the night. We took five 6 s-darks at the end of the
night. The different stages of the usual IR data reduction,
namely sky estimation and subtraction, frame centering
and stacking, including also dark subtraction and flat-
field division (we used the flat-field provided by the NTT
field division; reducing the offset residual to 0.7′).

Fig. 1. $K_S$-band finding chart based on 2MASS survey
image, showing the NTT/SOFI pointing field of view. The YSOs
of this area are marked according to their IR classifications
diamond/square/cross for resp. Class I/II/III IR source; see Lada 1991) from the ISO CAM mid-IR survey (Bontemps et al.
2001). The box indicates the area enlarged in Fig. 2a.

To differentiate between pure line emission knots and
continuum emission from stars (including scattered light)
we follow Davis & Elston (1995) who noted that the
narrow-band filter reduces the intensity of the field stars
by the ratio of the filter bandpasses (≈10), whereas the
intensity of the $H_2$ knots is only reduced by ≈2 (indeed
spectra of $H_2$ molecular shocks have other emission lines
in the $K_S$-band; see Smith 1995). We scale down the $K_S$
band image by the ratio of the filter bandpasses and the
ratio of the seeing to have continuum features appearing
with the same brightness in Fig. 2a and 2b. On the other
hand, $H_2$-shocks appear ≈5 times brighter in Fig. 2b than
in Fig. 2a and can thus be easily identified. The $H_2$-knots
detected are labelled on the $H_2$ contour map (Fig. 2b).

Table 1 gives the position of these knots with photometry
for a 1′-aperture from the 5σ-filtered images. Before ap-
plying wavelet filtering the $H_2$ image was convolved with a
Gaussian filter to have the same seeing as in the $K_S$-band
image. To obtain the $H_2$ magnitudes, we scaled up the $H_2$
intensities by the filter-band width ratio and applied the
magnitude zero-point of the $K_S$ image.

The knots A display a bow-shape structure, charac-
teristic of low-speed bow-shocks which produce such arcs
and limb-brightened structures of conical appearance
(Smith 1991). We also note in the $H_2$ image some diffuse emission
downstream of the bow-shock which may be related to the
excitation of $H_2$ in the pre-shock region of a J-shock.
We thus propose the knots A as the leading part of a jet
coming from the SW direction, and outlined by the up-
stream knots B. By contrast the knots C are displaced
from the direction of this jet, and moreover the knots C1–
C4 are clearly elongated, roughly along a NS direction.
We propose to explain these features by shocks coming from
the East and producing the arc C2-C1-C3, with the down-
stream knots C3 and C4. We will discuss in the following
section the possible exciting sources of these two jets.

To obtain an estimate of the $H_2$-shock velocity we com-
pare the observed near-IR photometry with the predic-
tions for planar molecular shocks (Smith 1993). We up-
data first these results for the NTT set of filters. We ex-
tract the filter transmission profiles from the plots pro-
vided on the SOFI web page, and convolve them to the
unfiltered molecular shock line fluxes (Michael D. Smith,
private communication). Zero points for $J−H$ and $H−K_S$
colors are derived by requiring the colors of A0 spec-
trum template (Pickles 1993) to be zero. We observe
$f(K_S)/f(H_2)≈1.4$ and $<2.0$ for the leading part of the
two jets, which must be compared to $f(K_S)/f(H_2)=2.0–
3.3$ (resp. 1.9–3.3) for J-shocks (resp. C-shocks) with veloc-
ity range 8–22 km s$^{-1}$ (resp. 20–45 km s$^{-1}$). This im-
ples J-shock (resp. C-shock) velocity $\lesssim 10$ km s$^{-1}$ (resp.
20 km s$^{-1}$), well below the $H_2$ dissociation velocity in
molecular cloud ($\sim 22$, $<47$ km s$^{-1}$ for resp. J, C-shock; see
Smith 1995). Hence, the $H_2$-line emission is really map-
Fig. 2. Deep near-IR images of the embedded HH objects discovered with NTT/SOFI. (a) K2-band image scaled so that continuum features from stars appear as bright as in the H2 v=1–0 S(1) narrow-band filter image. The pixel size is 0''29, and the grey color scale is linear. J-band (resp. H-band) detections above 5σ levels are shown with dashed (resp. continuous) contour levels (24.5, 23.5, 23.0 and 21.8, 21.2, 20.9 mag arcsec−2). (b) H2 v=1–0 S(1) narrow-band filter image (including the continuum emission). H2 line emission features appear brighter in this narrow-band image than in the previous broad-band one. (c) H2 v=1–0 S(1) narrow-band filter image (including the continuum emission). H2 line emission features appear brighter in this narrow-band image than in the previous broad-band one. The first (resp. second) arrow joins the barycenter of the knots A–B (resp. C) and the Class I protostar YLW15 (resp. IRS54). The first arrow corresponds also to the symmetry axis of the knots A–B.

ping the bow-shock: we can exclude the scenario where this emission would come only from the low-velocity wing of a fast dissociative bow-shock located downstream, with strong iron lines in the J and H bands tracing the apex. These low-velocity embedded H2-shocks are reminiscent of the low excitation HH objects already observed in the optical in this dark cloud. From the intrinsic color of low-velocity H2-shocks, (J − H)0≈0.8, and assuming the reddening law quoted by Cohen et al. (1981), we estimate the extinction for knot C1: AV=9.09×[(J−H)−(J−H)0]≈23. This large visual extinction explains the non-detection by previous optical surveys. It will be possible to measure directly Av by J, H-band spectroscopy using [Fe II] lines at 1.25 µm, 1.64 µm, which arise from the same atomic upper level.

Table 1. H2-knot positions and magnitudes

| Knot names | αJ2000 | δJ2000 | J | H | Ks | H2 | f(Ks) f(H2) |
|------------|--------|--------|---|---|----|----|------------|
| A1 | 43°4 | 31°45′4 | − | 23.7 | 19.3 | 17.1 | 1.4 |
| A2 | 43°3 | 31°44′0 | − | − | 20.1 | 17.9 | 1.3 |
| B1 | 42°9 | 31°56′4 | − | 19.7 | 17.6 | 1.4 |
| B2 | 42°8 | 32°05′1 | − | 20.0 | 17.7 | 1.2 |
| C1 | 43°0 | 32°06′9 | − | 21.8 | 18.8 | 0.6 |
| C2 | 43°2 | 32°13′5 | − | − | 19.6 | 17.5 | 1.4 |
| C3 | 42°7 | 32°07′7 | − | 19.6 | 17.8 | 2.0 |
| C4 | 42°8 | 32°07′2 | 22.2 | 19.7 | 17.8 | 1.8 |
| C5 | 43°0 | 32°04′0 | − | 20.0 | 17.9 | 1.4 |

3. Discussion on the exciting sources

The optical survey of HH objects in Taurus has shown that their frequency decreases rapidly with the age of the YSO, from Class I sources to Class II sources (Gómez et al. 1997), i.e. from evolved protostars to classical T Tauri stars. This result is consistent with the decrease of the CO outflows observed from the Class 0 sources to the Class I sources (Bontemps et al. 1997). To find the exciting source candidates of the HH objects reported here, it is thus reasonable to look for YSOs with IR excesses. On the basis of the HH feature morphology, we proposed in the previous section shocks coming from the East (resp. SW) to explain the shape of knots C (resp. A–B). We checked by constructing a color-color diagram of the sources detected...
in our deep observation, that there is no new embedded YSO with IR excess in these directions. Two known YSOs are Eastward (see Fig. 2c) the Class II source GY350, and the Class I protostar IRS54. We propose to associate knots C with IRS54, the agreement with the knots shape looking better (see Fig. 2c). Strong $H_2$ $v=1-0$ S(1) line emission was detected in the IRS54 spectrum (Greene & Lada 1996). It is unresolved in our $H_2$ image, which shows only scattered light Eastward. To our knowledge this source has never been included in a CO outflow survey.

Fig. 2c shows that the Class I protostar YLW15, also called IRS43, is on-axis of the knots A–B, $\sim 10^\circ$ away (0.4 pc for d=140 pc). This evolved protostar is a radio source, and was recently announced to be a subarcsecond radio binary (Girart et al. 2000). The main radio component, YLW15-VLA1, is spatially extended with a position angle of $25^\circ \pm 2^\circ$ (one sigma error), and Girart et al. proposed it to be a thermal radio jet candidate. The position angle (PA) of the knot chain, $22.3^\circ \pm 2^\circ$, is compatible with the PA of this jet candidate within errors (Fig. 2). As the probability for a coincidence by chance between these PAs is very low ($2\times1.645^2/180^\circ=0.037$), the identification of YLW15 as the exciting source of knots A–B is likely. Fig. 3 displays the position of the HH objects of this dark cloud. The $[S\text{II}]$ knot HH224NW1 (Gómez et al. 1998) was associated with the complex HH object HH224. We note however that HH224NW1 is displaced from the axis of HH224, and that the PA of YLW15 is $23.4^\circ$, thus also compatible with the orientation of the thermal jet candidate. HH224NW1 may then be related to a counterjet of YLW15. This association between YLW15 and these HH objects strengthens the proposal of Girart et al. for a thermal jet in this object. Moreover the alignment with the HH objects moving at $V \leq 10-20$ km s$^{-1}$ implies that this jet is not precessing at least on timescale $\sim (2-4) \times 10^4$ yr.

These observations confirm that HH objects excited by Class I protostars may be hidden by large extinctions in the optical, but can be easily unveiled and studied by deep near-IR observations. Embedded HH objects are probably very common, and it is essential now to obtain a reliable census, for instance to quantify the role of outflows in maintaining a high level of turbulence in molecular clouds and regulating star formation (Matzner & McKee 2000).

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