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First results of an unbiased H_2 survey for protostellar jets in Orion A

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Abstract. We are conducting an unbiased search at $\lambda 2.12\mu$m for embedded molecular hydrogen jets thought to be associated with very young stellar objects, deeply embedded in dense cores in the Orion A molecular cloud. As a first result, we show a 0.4×0.5 degree mosaic centred on the L 1641-N complex, revealing a number of previously unknown knots and chains of H_2 emission. A 5×5 arcmin close-up of L 1641-N shows it to be a very active region, with at least one parsec-scale jet originating in the small embedded cluster: we also show 10μm imaging to help identify the outflow source. Elsewhere in the mosaic, several knots in the HH 34 jet are detected for the first time in H_2, and a new, deeply embedded jet is discovered next to it. These preliminary results demonstrate the power of H_2 imaging surveys in studying the large-scale role of jets and outflows in star formation.

Key words: ISM: jets and outflows – infrared: ISM: lines and bands – stars: formation – ISM: individual objects: L 1641-North – ISM: individual objects: HH 34

1. Introduction and goals of the survey

Molecular outflows are an important tracer of ongoing star formation, and sensitive surveys of entire cloud complexes would allow us to study the statistical ubiquity of outflows and determine their cumulative "feedback" impact on the parent cloud. However, the relatively low spatial resolution of single-dish millimetre surveys can result in significant ambiguity in crowded regions, and improvements of ∼10–100 are possible by searching for optical/near-IR emission from shocks as the outflow interacts with the cloud. In particular, H_2 emission at 2.12μm can reveal jets still deeply embedded in cloud cores from which stars are presently forming, and large-scale surveys in this line are now possible using large-format IR cameras.

One of the most comprehensively studied molecular complexes is the Orion A (L 1641) cloud at ∼ 500 pc. In addition to extensive optical, IR, and x-ray studies (e.g. Strom et al. 1989a, Strom et al. 1989b, Strom et al. 1990, Allen 1995, and references therein), the cloud was recently surveyed in the CS (1–0) transition by Tatematsu et al. (1993), who found 125 dense cloud cores thought to be locations for ongoing and/or future star formation. We have begun a sensitive H_2 survey of the same region with the following goals:

- To determine the frequency of H_2 jets in the dense cores and relate them to CO outflows, in order to examine the overall impact of jets and outflows on a cloud complex
- To see whether jets occur preferentially in smaller, isolated cores, or also in regions of cluster-mode star formation
- To search for deeply embedded Class 0 protostars as jet driving sources, similar to HH 211 (McCaughrean et al. 1994) and HH 212 (Zinnecker et al. 1996)

2. Observations

Our initial observations were carried out on 1996 December 26 using the Omega-Prime wide-field near-IR camera (McCaughrean et al., in prep.) on the Calar Alto 3.5-m telescope. The camera uses a 1024×1024 pixel HgCdTe array: at 0.4 arcsec per pixel, the field-of-view is 6.7×6.7 arcmin. Images were taken through a 1% filter centred on the v=1–0 S(1) line of H_2 at 2.12μm and a corresponding broad-band K′ filter (1.944–2.292μm) in order to discriminate line and continuum sources. A total of 64 overlapping images were combined to make 4×5 position mosaics centred on L 1641-N, covering a total of 1623×2005 arcsec (i.e. ∼0.4×0.5°, or 3.5×4.4 parsec assuming 450 pc to Orion A), ∼ 20% of the region surveyed by Tatematsu et al. (1993). In the 2.12μm filter, the net integration time was 8 min in the central part of the mosaic and 4 min at its edges; at K′, the corresponding times were 1 min and 30 sec. We reach a 5σ limiting H_2 surface brightness of $\sim 10^{-18}$ W m^{-2} arcsec^{-2} (K′∼17 for continuum point sources). Standard data reduction

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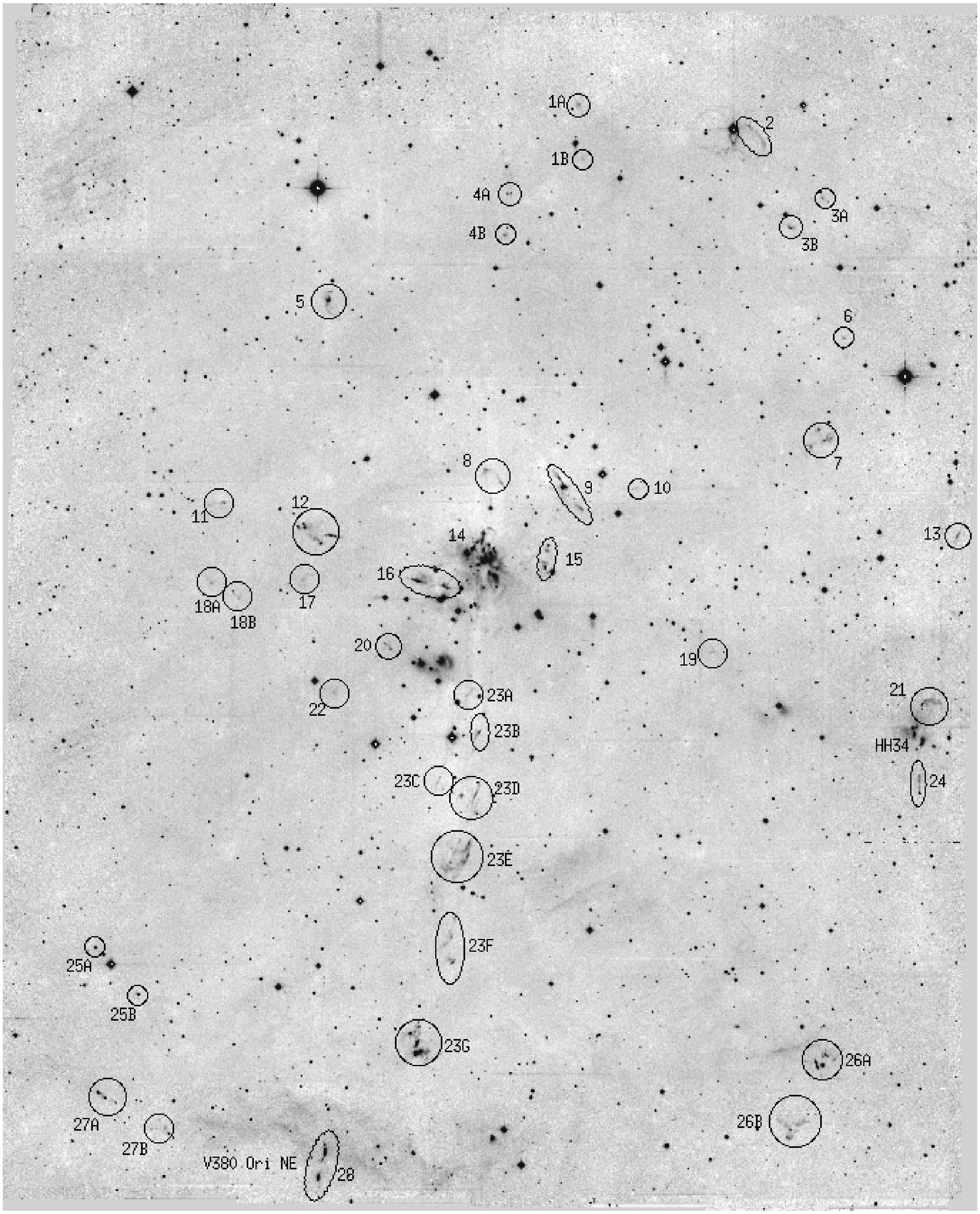

Fig. 1. Mosaic of a ∼0.4×0.5° region centred on the L 1641-N complex at 2.12μm. Continuum emission has not been subtracted, but a corresponding continuum image has been used to identify pure H_2 emission objects, as marked by circles/ellipses. The nebulosity at the centre of the image is a complex mixture of continuum and H_2 line emission. The image is centred at $05^h\,36^m\,18.2^s$, $-06°\,23'\,22''$ (J2000.0).

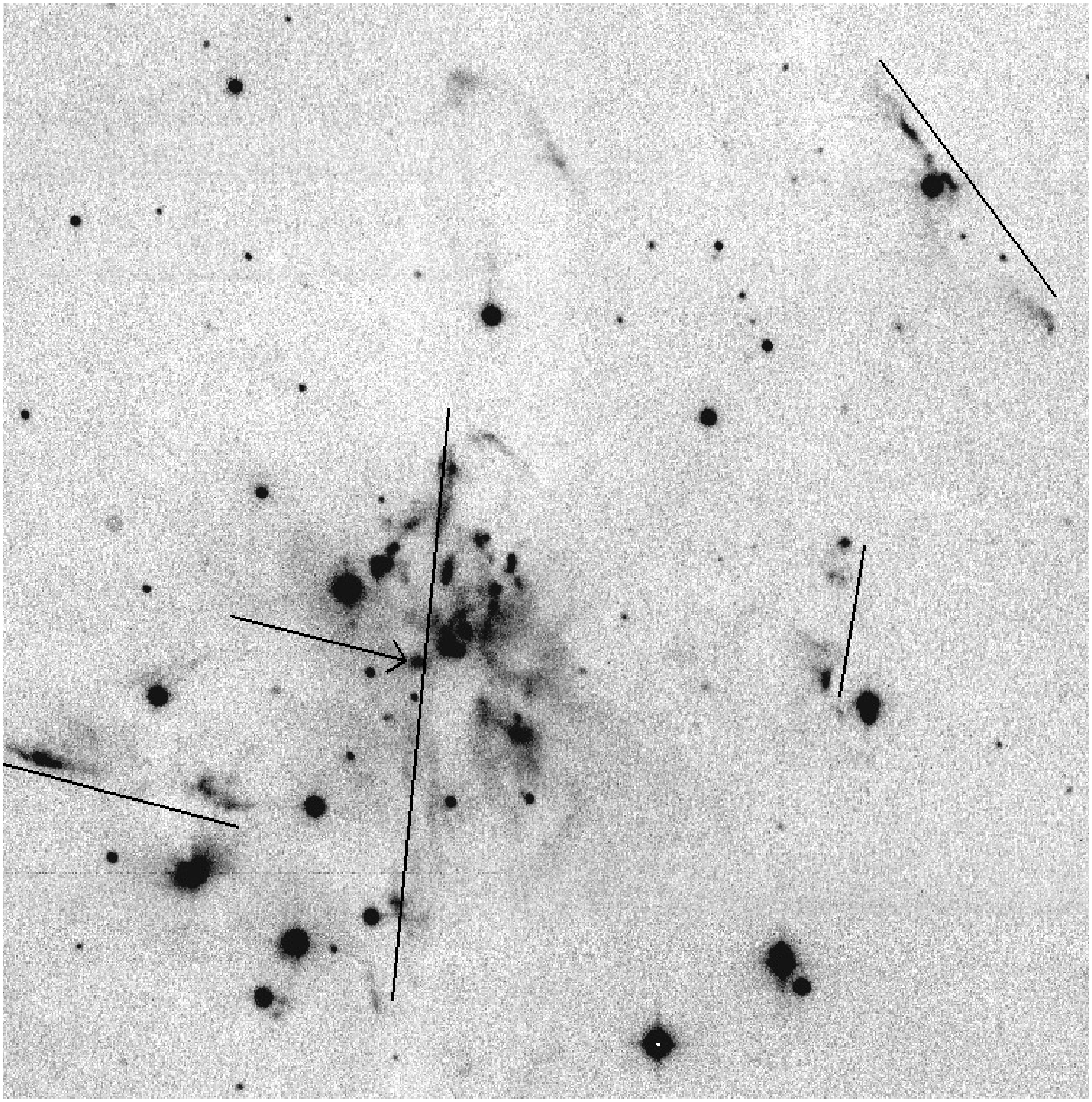

Fig. 2. A ∼5×5 arcmin closeup of the L 1641-N region. Lines show chains of H_2 knots; the arrow marks the location of the proposed outflow source, a small continuum nebulosity coincident with N15 of Chen et al. (1993) (see text).

techniques were used to sky subtract, flat field, and mosaic the data (McCaughrean et al. 1994).

3. Results

The full 2.12μm mosaic is shown in Fig. 1. Careful comparison with the corresponding broad-band K′ image leads to the identification of a number of knots and chains of pure H_2 emission, which are marked with circles/ellipses in Fig. 1, and whose coordinates are listed in Table 1. In several cases, we have grouped apparently related sources, although these groupings are not yet proven to be physically associated. While it is premature to identify these structures with jets *per se*, it seems likely on morphological grounds that most are associated with shocked molecular hydrogen. Small-scale instabilities and short cooling lengths in shocks generally lead to narrow, elongated, and clumpy emission knots as seen here, while fluorescence due to large-scale UV radiation fields leads to characteristically diffuse and relatively unstructured emission (Gatley et al. 1987). Additional support for the assumption that the H_2 emission is caused by shock excited gas is provided by the fact that some of the H_2 features in the northern part of the mosaic can be identi-

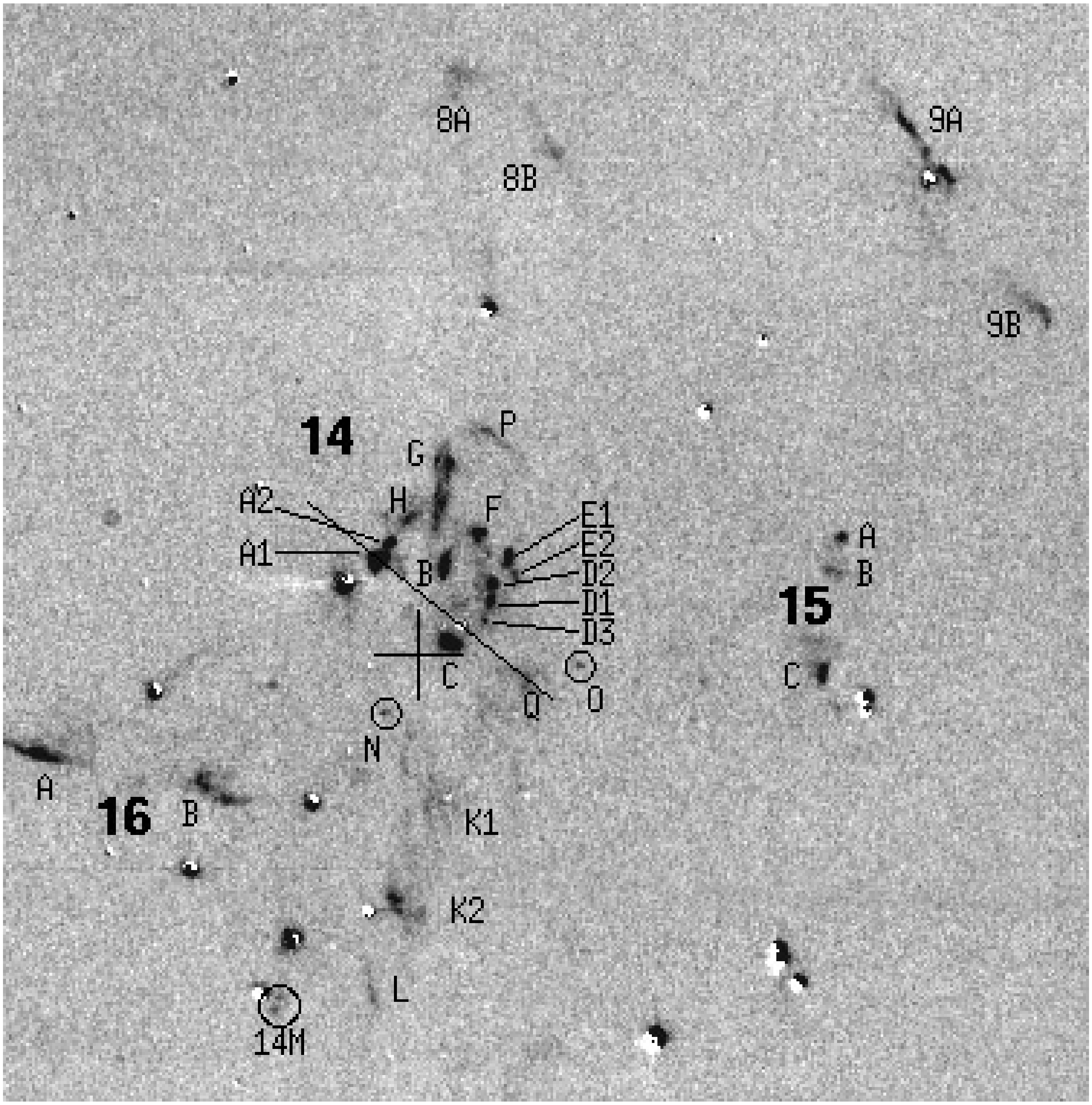

Fig. 3. Continuum-subtracted 2.12μm image of the L 1641-N region ($\sim$5$\times$5 arcmin). The cross marks the position of the K$'$ continuum source, thought to be the origin of the N-S flow. A second outflow axis including Knot A of Davis & Eislöffel (1995) is indicated with a line.

fied with *bona fide* optical HH objects (HH 299, HH 301–304; see Table 1, and Reipurth 1985, Reipurth et al. 1998).

At the heart of the mosaic lies the L 1641-N complex, where Strom et al. (1989a) found a small cluster of infrared sources. Hodapp & Deane (1993) studied the region in detail, and described a group of relatively bright stars found in a wider field around the centre, showing them to be young, with a median age ~ 3–5×10^5 years. The spread in ages suggests that star formation has been going on for about 10^6 years, and as a signpost of more recent, ongoing star formation, Fukui et al. (1988) found a north-south oriented bipolar molecular outflow originating in the small embedded cluster, with both lobes extending over ~ 0.2 pc or ~ 90 arcsec at Orion. Our H_2 mosaic shows this outflow to be part of a much larger, giant flow system, with a chain of H_2 emission knots extending southward and almost reaching the edge of our mosaic some 2 pc from the source (knots 23A–G). A chain of several possibly related fainter knots is also seen to the north of L 1641-N (4A, 4B). Figs. 2 and 3 show line+continuum and pure line images of the central region respectively, revealing a mixture of diffuse continuum nebulosity and relatively compact H_2 features. Several elongated emission-line structures are marked, some of which

Table 1. Positions of the H_2 features

Name[a]	RA(2000)	Dec(2000)	Remarks
SMZ 1A	5 36 09.2	−6 09 27	
1B	5 36 08.7	−6 10 54	
2	5 35 49.0	−6 10 13	
3A	5 35 41.6	−6 11 57	
3B	5 35 45.2	−6 12 44	
4A	5 36 16.9	−6 11 56	
4B	5 36 17.3	−6 13 04	
5	5 36 37.0	−6 14 57	HH 304[b]
6	5 35 39.1	−6 15 43	
7	5 35 41.7	−6 18 33	
8	5 36 18.1	−6 19 47	HH 303[b]
9	5 36 10.0	−6 19 58	HH 299[b]
10	5 36 02.1	−6 20 00	
11	5 36 48.6	−6 20 40	HH 302[b]
12	5 36 37.8	−6 21 26	HH 301[b]
13	5 35 26.3	−6 21 14	HH 85E[c]
14	5 36 19.3	−6 22 07	L 1641-N
15	5 36 12.1	−6 21 56	
16A	5 36 26.5	−6 22 41	
16B	5 36 23.1	−6 22 48	
17	5 36 39.2	−6 22 42	
18A	5 36 49.8	−6 22 46	
18B	5 36 46.6	−6 23 11	
19	5 35 53.3	−6 24 33	
20	5 36 29.6	−6 24 29	
21	5 35 28.8	−6 25 47	
22	5 36 35.5	−6 25 49	
23A	5 36 20.4	−6 25 47	
23B	5 36 19.4	−6 26 52	
23C	5 36 23.7	−6 28 12	
23D	5 36 20.4	−6 28 40	
23E	5 36 21.3	−6 30 28	
23F	5 36 22.2	−6 32 38	
23G	5 36 25.5	−6 35 35	
24	5 35 30.0	−6 28 04	
25A	5 37 01.8	−6 32 59	
25B	5 36 56.7	−6 34 18	
26A	5 35 40.1	−6 35 53	HH 86[c]
26B	5 35 43.7	−6 37 41	HH 87[c], HH 88[c]
27A	5 37 00.3	−6 37 11	
27B	5 36 54.3	−6 37 57	
28	5 36 36.3	−6 38 50	V 380 Ori NE

[a] as per recommendation of the IAU Nomenclature Committee
[b] see Reipurth et al. 1998
[c] see Devine et al. 1997

extend into the larger mosaic. The most prominent of these is the inner section of the large-scale, roughly north-south jet associated with the L 1641-N molecular outflow (knots 8, 14 G, B(?), K1, K2, L; see also Davis & Eislöffel 1995). The arrow in Fig. 2 marks a small patch of continuum emission (Source N15 of Chen et al. 1993) that lies at the base of both lobes of the H_2 flow. A new 10μm image of this region was obtained using the TIMMI system on the ESO 3.6-m telescope on December 1st, 1996, and reveals a bright mid-IR point source (flux 0.4 Jy) coincident with the near-IR nebulosity (Fig. 4). We suggest that

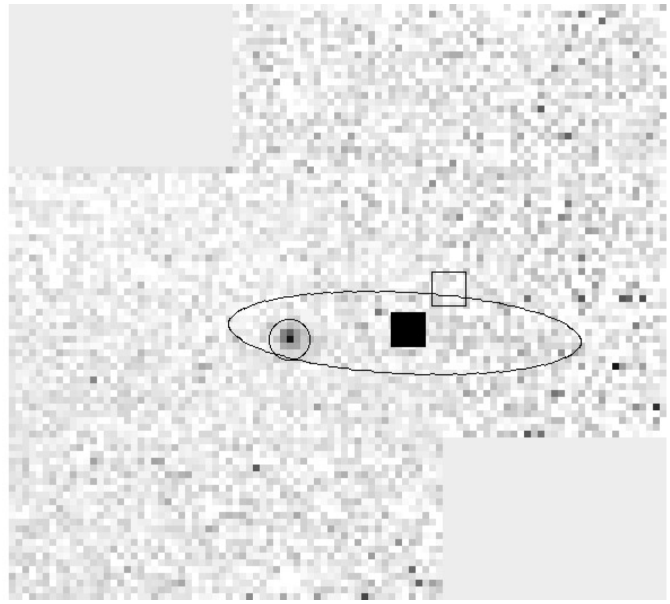

Fig. 4. 10μm image (49×44 arcsec) of the L 1641-N source region showing the proposed outflow source (inside open circle). The size of the circle corresponds to its estimated positional accuracy of ∼2 arcsec. Within these errors the 10μm source coincides with source N15 of Chen et al. (1993) (see text). Also marked are the IRAS source position (filled box; ellipse indicates positional error) and the 2.7-mm continuum emission peak (open box; size of the box indicates positional error). Although the 10μm source is coincident with source N15, it is not possible to unambiguously attribute the IRAS fluxes to either N15 or the 2.7-mm continuum source, since the IRAS source position is consistent with both.

this 10μm source is a deeply embedded young object which illuminates the compact reflection nebulosity, as well as driving the jet and outflow. For reference, the locations of the nominal central IRAS source, IRAS 05338−0624, and a 2.7-mm dust continuum emission peak previously proposed as the outflow source (Chen et al. 1993, 1995) are also marked.

However, in addition to the main jet, there are many other knots of H_2 emission in this central region (14A–F, H, M–Q). Their origin is not clear, although possible explanations include the interaction of the less collimated molecular outflow with the walls of a cavity, or the presence of additional jets and outflows emanating from the core. Evidence for the existence of a second outflow is in fact seen in maps of the high-velocity molecular gas (Fukui et al. 1988; Wilking et al. 1990): the redshifted lobe clearly comprises two well-separated parts, one of which lies south of the outflow source, coincident with the southern lobe of the main H_2 jet, while the other lies to the west of the IRAS source. The blueshifted lobe also shows substructures, with an extension to the NE of the IRAS source (Wilking et al. 1990), and a bright bow-shaped H_2 knot (knot A1 = knot A of Davis & Eislöffel 1995) seen in Fig. 3 also suggests a second outflow at a position angle of ∼45–60 degrees, possibly including also knots C and Q. Thus we propose that the L 1641-N complex includes at least two independent outflows. Detailed

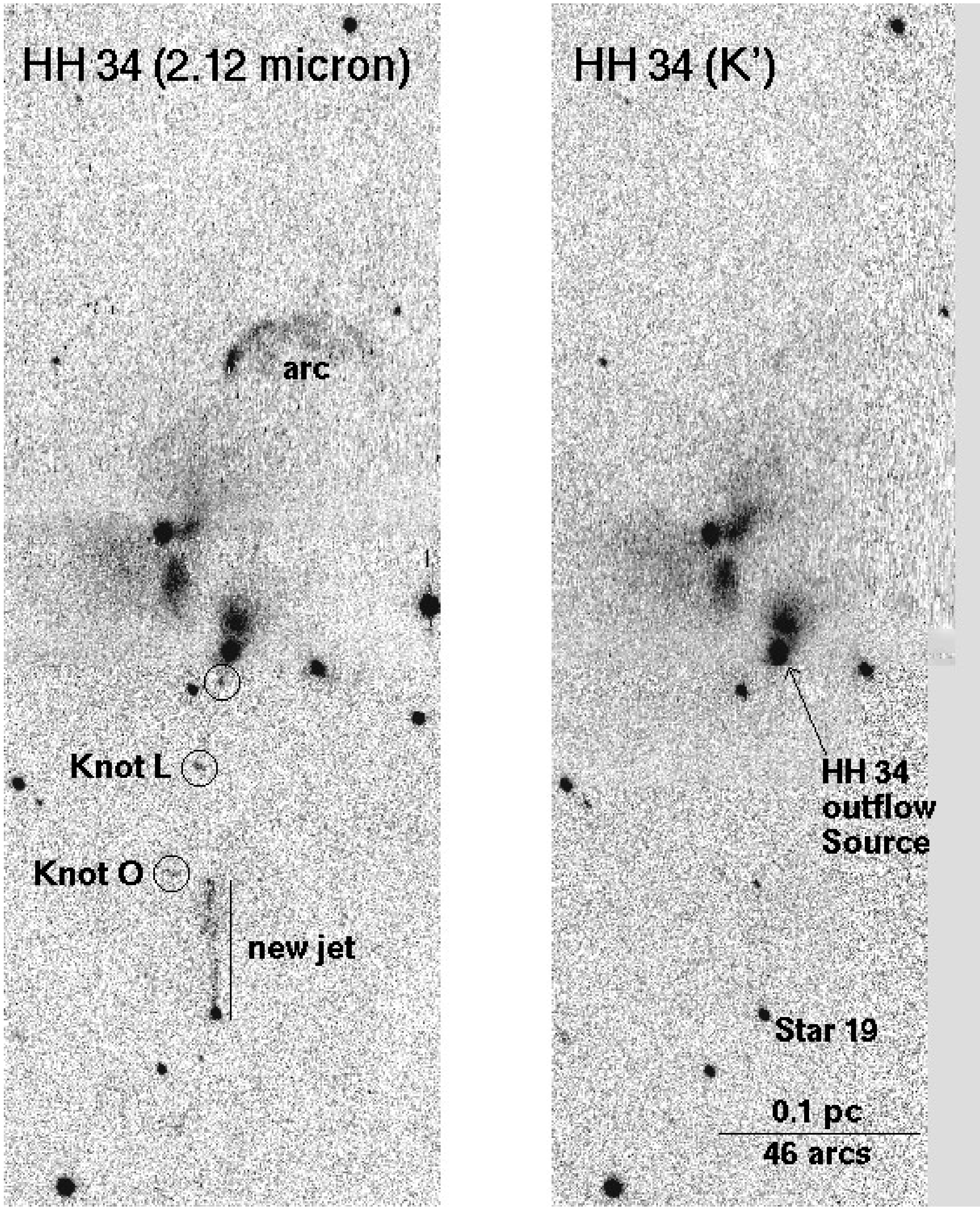

Fig. 5. The region around the HH 34 jet in H_2 (left) and in K′ continuum (right). The H_2 image covers ∼1.8×4.5 arcmin. H_2 knots in the HH 34 jet are circled.

mm-interferometry and proper motion measurements of the H_2 knots should help clarify this situation.

Finally, returning to the full mosaic (Fig. 1), we are able to relate several other chains of H_2 knots to known outflows. A curving H_2 feature (object 28) at the southern edge of the mosaic, extending roughly north-south, is probably an infrared counterpart to the known V380 Ori NE molecular outflow (Morgan et al. 1991). To the west, H_2 emission is seen along ∼ 2 pc of the HH 34 superflow, associated with the optical Herbig-Haro objects HH 86–88 and HH 85-E (object 26 and 13; see Devine et al. 1997). In addition, H_2 emission is seen for the first time from the HH 34 jet itself (Fig. 5, cf. Stapelfeldt et al. 1991; Zealey et al. 1993). H_2 emission is seen corresponding to the optical knots O and L (Heathcote & Reipurth 1992), and while the large bow shocks HH 34 and HH 34-N are not detected, a bright extended arc of H_2 emission (object 21) is seen in the northern lobe, just south of the optical HH 34-N. Interestingly, a linear H_2 feature (object 24) is seen adjacent to the location of the HH 34 bow-shock. Previously thought by Zealey et al. (1993) to be part of the HH 34 flow, this linear feature is now clearly revealed to be a separate jet, oriented north-south and appearing to originate at Star 19 of Heathcote & Reipurth (1992). Since, unlike HH 34, it has no optical counterpart, its presence may indicate a spread in the ages of young stars in this compact region.

4. Conclusions

The first results of our survey show that shocked H_2 emission is common in the Orion A cloud, and suggest that much of it may be associated with jets driven by young sources embedded in the cloud. The detection of a previously unknown jet immediately adjacent to the well-studied HH 34 demonstrates that near-IR imaging provides a powerful tool with which to search for deeply embedded outflows, and in combination with other observations (10μm imaging, millimetre mapping, and interferometry), we will be able to relate the properties of young outflows and their sources. The completion of our H_2 survey of the entire cloud complex should reveal even more jets, and will allow us to make a statistical assay of the number of jets compared with, for example, the number of dense cloud cores, and thus assess the roles outflows play in the formation and evolution of stars, in particular that of "feedback" in terms of turbulence and disruption injected into the parent cloud.

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