New Herbig–Haro Objects and Giant Outflows in Orion

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ABSTRACT
We present the results of a photographic and CCD imaging survey for Herbig–Haro (HH) objects in the L1630 and L1641 giant molecular clouds in Orion. The new HH flows were initially identified from a deep Hα film from the recently commissioned AAO/UKST Hα Survey of the southern sky. Our scanned Hα and broad band R images highlight both the improved resolution of the Hα survey and the excellent contrast of the Hα flux with respect to the broad band R. Comparative IVN survey images allow us to distinguish between emission and reflection nebulosity. Our CCD Hα, [Sii], continuum and I band images confirm the presence of a parsec–scale HH flow associated with the Ori I–2 cometary globule and several parsec–scale strings of HH emission centred on the L1641–N infrared cluster. Several smaller outflows display one–sided jets. Our results indicate that for declinations south of -6 in L1641, parsec–scale flows appear to be the major force in the large–scale movement of optical dust and molecular gas.

Key words: surveys: stars: formation – ISM: jets and outflows

1 INTRODUCTION
The process of star formation is a highly disruptive event where both infall and outflow of material occur simultaneously in the production of a protostellar core. The outflow phase is characterised by the impact of high velocity winds with the surrounding interstellar medium which manifest as bipolar molecular outflows, Herbig–Haro (HH) objects and jets. Multi–wavelength observations have shown HH objects and jets to be regions of shock–excited gas emitting Hα (λ6563), [Oi] (λλ6300,6363) and [Sii] (λλ6716,6731) in the visible and H2 (2.12μm) in the infrared. Their energy sources range from deeply embedded protostars to optical T–Tauri and Herbig Ae/Be stars.

With the introduction of large format CCD detectors, wide–field imaging has shown HH flows are more abundant and an order of magnitude larger than previously thought. Recent narrow band imaging of the NGC 1333 star–forming region (SFR) by Bally, Devine & Reipurth (1996) found a high concentration of HH objects within a 1/4 square degree region. A similar result was found by Yu, Bally & Devine (1997) who conducted a near-infrared H2 (2.12μm) survey of the OMC–2 and OMC–3 regions in Orion. Based on well–studied flows such as HH 1/2, HH 34 and HH 46/47, it was generally thought their extent (∼ 0.3 pc) was typical of outflows from low–mass stars. Bally & Devine (1994) were the first to question this view with their suggestion that the HH 34 flow in Orion is actually 3 pc in extent. Their idea was confirmed with deep CCD imaging and proper motion studies of individual knots (Devine et al. 1997). To date, around 20 giant (>1 pc) HH flows have been associated with low–mass stars (Eislöffel & Mundt 1997; Reipurth et al. 1997).

A large number of giant HH flows (and their small–scale counterparts) may have dramatic effects on the stability and chemical composition of a giant molecular cloud (GMC). It has been suggested that outflows may provide a mechanism for self–regulated star–formation and large–scale bulk motions within GMCS (Foster & Boss 1996). It is therefore important to gain information on the distribution of outflows and particularly giant flows within SFRs. The new Anglo–Australian Observatory (AAO) and United Kingdom Schmidt Telescope (UKST) Hα Survey of the Southern Galactic Plane (Parker & Phillipps 1998a) will be beneficial for such studies as it provides an unbiased search for new HH objects over entire SFRs with its wide–field and high resolution capabilities.

In this paper we concentrate on a search for new HH objects in the first, deep Hα film of the Orion SFR. The distance to the Orion region lies between 320 to 500 pc (Brown, De Geus & De Zeeuw 1994). Here we adopt a distance of 470 pc based on known HH objects in the region (Reipurth 1999). Strong emission and reflection nebulosity in the region makes searching for HH objects difficult. Previous attempts at surveys for faint red nebulosities in L1630 and
L1641 have used standard broad band IIIaF R plates (IIIaF emulsion and RG630 filter), which were limited to subregions clear of high background emission (Reipurth 1985; Malin, Ogura & Walsh 1987; Reipurth & Graham 1988; Ogura & Walsh 1991). The new, deep fine resolution Hα films enable us to conduct a more complete survey for emission–line nebulosities for consequent follow–up observations.

In Section 2 we present a brief introduction to the specifics of the Hα survey and details on observations and data reduction. Results are presented in Section 3 where individual objects are discussed. In Section 4 we make some general conclusions and references to future work.

2 OBSERVATIONS AND DATA REDUCTION

2.1 The AAO/UKST Hα survey

Under the auspices of the AAO, the UKST has recently embarked on a new Hα survey of the Southern Galactic Plane, Magellanic Clouds and selected regions. No systematic high resolution Hα survey has been carried out in the southern hemisphere since the pioneering work of Gum (1955) and Rodgers, Campbell & Whiteoak (1963). With the increase in resolution and sensitivity of differing wavelength technologies, there has been the need to perform an Hα survey with similar attributes.

The unusually large, single–element Hα interference filter is centred on 6590Å with a bandpass of 70Å. It is probably the largest filter of its type in use in astronomy. Coated onto a full field 356mm × 356mm RG610 glass substrate, the 305mm clear circular aperture provides a 5.5 field–of–view. Further details of the filter properties and specifications are given by Parker & Bland–Hawthorn (1998). The detector is the fine grained, high resolution Tech Pan film which has been the emulsion of choice at the UKST for the last 4 years. This is due to its excellent imaging, low noise and high DQE (e.g. Parker, Phillips & Morgan 1995; Parker et al. 1998). Tech Pan also has a useful sensitivity peak at Hα as it was originally developed for solar patrol work. Though electronic devices such as CCDs are the preferred detector in much of modern astronomy, they cannot yet match the fine resolution and wide–field coverage of the Tech Pan film and UKST combination.

Typical deep Hα exposures are of 3 hours duration, a compromise between depth, image quality and survey progress as the films are still not sky–limited after this time. The Southern Galactic Plane survey requires 233 fields on 4 degree centres and will take 3 years to complete. Initial survey test exposures have demonstrated that the combination of high quality interference filter and Tech Pan film are far superior for the detection and resolution of faint emission features near the sky background than any previous combination of filter and photographic plate used for narrow band observations (Parker & Phillips 1998a). It is the intention that the original films will be digitised using the Royal Observatory Edinburgh’s SuperCOSMOS facility (Miller et al. 1992). It is planned to release a calibrated atlas of digital data to the wider astronomical community as soon as possible.

2.2 Photographic astrometry and image reduction

For the Orion region, a deep 3–hour Hα exposure was obtained on 1997 December 2nd during a period of good seeing. The plate (HA 17828) was centred at 05°36′.04°00′ (1950) and designated grade A based on standard UKST visual quality control procedures by resident UKST staff. Three independent visual scans of the film were carefully made by QAP, SLM and WJZ using an eyepiece and later a 10× binocular microscope. HH objects display a wide range of morphologies including knots, arcs and jets. A combined list of such features was produced and served as the basis for subsequent astrometry. The new Hα images were then compared with deep non–survey UKST IIIaJ, IIIaF and IVN broad band copy plates of the same field to confirm the objects as true emission–line sources. The plates used and their characteristics are presented in Table 1.

Crude positions for each object were first determined using simple XY positions from the film and transformed to B1950 coordinates by use of the UKST program PLADAT. Accurate positions were then obtained by using SkyView FITS files of the surrounding region. This resulted in a positional accuracy within 2 for each object. Digitized images of each source were then made using a video digitising system (Zealey & Mader 1997; 1998). This enabled us to process images via un–sharp masking and histogram enhancement to recover the original detail as seen on the TechPan film.

2.3 CCD observations

2.3.1 Optical

As the Orion region shows highly structured background emission, it is important we distinguish between photo-ionised filamentary structures and bona fide HH objects. This can be accomplished with Hα and [SⅡ] images by noting that HH objects usually have [SⅡ]/Hα ratios > 1 compared to [SⅡ]/Hα < 1 for emission associated with HH regions. We obtained narrow and broad band images of HH candidates at the Australian National University 1.0m telescope at Siding Spring Observatory during various periods in January–April 1998. Imaging was done with a 2048 × 2048 TEK CCD mounted at the f/8 Cassegrain focus. The 06 per pixel gave a field–of–view of 2048 × 2048. The seeing conditions during usable time was typically < 3. Narrow band filters used were [OⅢ] (λ5016; ∆λ 25Å), Hα (λ6565; ∆λ 15Å), [SⅡ] (λ6732; ∆λ 25Å) and red continuum (λ6676; ∆λ 55Å). The Hα filter also transmits the [NⅡ] (λ6548/6584) lines. We used a standard Kron–Cousins filter for the I band observations.

Typical exposure times were 300s and 900s for broad and narrow band frames respectively. Flat fields were obtained by illuminating the dome with a halogen lamp. All frames were reduced in a similar fashion with IRAF*, where 25 median combined bias frames were subtracted from source frames prior to flat fielding. Individual source frames

* IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
were median combined to produce the final images. In several instances, we were not able to obtain corresponding continuum frames to our CCD Hα and [SⅡ] images. As major HH emission lines do not fall within the spectral response curve of the RG715 + IVN filter/emulsion combination (Δλ = 6000Å–9100Å), we use photographic IVN images to serve as continuum images where needed.

2.3.2 Near–infrared

In January 1993 several HH complexes (including Ori I–2) were imaged using IRIS, the AAO infrared camera and low resolution spectrograph. The 128 × 128 format array has 60μm pixels which when used in the f/15 imaging mode provided a spatial resolution of 194 per pixel and a 41 × 41 field–of–view. Each source was observed through a 1% bandpass filter centred on the H2 v = 1 − 0 S(1) transition at 2.12μm. Continuum images were made using a 4% bandpass filter at 2.24μm. Individual frames were linearised, flat fielded against a dome flat and sky subtracted before being combined and calibrated using the IRIS image reduction package known as YOGI-FIGARO. A mosaic of twelve frames, each of five minutes in length were combined to form the final images.

3 RESULTS

In Table 2 we list new HH objects identified by our narrow band CCD imaging of candidates identified from the Orion Hα plate. Several of the new objects were identified by Reipurth (1985) as candidate HH objects from his ESO R film survey of the Orion region. Objects independently discovered by the CCD imaging of Reipurth, Bally & Devine (1998; hereafter R98) are indicated. In addition to brief comments about their nature and location, Table 2 also suggests possible energy sources based on evidence presented.

3.1 New objects in L1630

Our survey region of the southern portion of L1630 is shown in Fig. 1. The rest of the cloud complex extends several degrees to the north–east of the figure. A diffuse shell of HII surrounds the multiple OB system ζ Ori. Ogura & Sugitani (1998) list many of these globules as remnant clouds which may be sites of retarded star formation. The bright HII regions NGC 2024 and IC 434 (which includes The Horsehead Nebula) outlines an ionisation front between the southern portion of L1630 and ζ Ori. This ionisation front extends towards the open cluster NGC1981 which approximately marks the division between L1630 and L1641. The position of the new HH flows in the region are indicated.

3.1.1 HH 289 (Figs 1–3)

Located on the north–western outskirts of IC 434, the bright rimmed cometary globule Ori I–2 is host to the low–luminosity (Lbol = 13 L⊙) IRAS source 05555–0416, which drives both a bipolar CO and near–infrared molecular hydrogen outflow (Sugitani et al. 1989; Cernicharo et al. 1992; Hodapp 1994). The IRAS source is also associated with a H2O maser (Wouterloot & Walmsley 1986; Codella et al. 1995).

A comparison between our scanned Hα and IVN images (Figs 2a,b) identifies a chain of emission–line objects (objects 2–5) extending to the east of the globule. To the west, we see another emission–line feature (object 1) which appears as an extension of faint emission seen in the IVN image. The Hα+[SⅡ] images (Figs 3a,b) confirms the presence of a HH flow, designated here as HH 289. In the central part of the globule, the Hα+[SⅡ] and H2 images (Figs 3b,c) show two faint [SⅡ] knots (HH289 A/B) which mirror the position of the H2 emission. With the exception of knot C, all knots appear [SⅡ]–bright. Knots D–F show large arc–like morphologies which open towards the IRAS source. This gives the impression of a bubble surrounding the eastern side of the globule which may represent an interface between the outflow and the UV radiation field from ζ Ori, which is 42 to the east of Ori I–2.

From the distribution of optical and near–infrared emission about the IRAS source (Figs 3b,c), we suggest it is the driving source of the HH 289 outflow. The chain extends 551 from the IRAS source making the lobe 1.23 pc in projection. This puts the Ori I–2 flow in the class of parsec–scale flows from low–mass stars (Reipurth, Bally & Devine 1997).

As HH objects typically display tangential velocities in the order of 150 km s−1 (i.e., Mundt 1988), the age span of the optical knots ranges from 530 yr (knot A), to 8100 yr (knot F). The projected lengths of the (redshifted) CO, H2 and optical HH flows are 40 (0.09 pc), 80 (0.18 pc) and 551 (1.23 pc) respectively. Apart from knot A, we do not see any evidence of HH emission associated with the blueshifted CO lobe, which we expect will be very faint due to the tenuous medium on the western side of the globule. Deeper [SⅡ] and/or [OⅢ] images of the western side of the globule may reveal fainter emission.

In Fig. 3b, we note the appearance of a tube–like feature extending out of the western side of the globule (object 1 in Fig. 2a). It is well aligned and mirrors the inner [SⅡ] and H2 knots with respect to the IRAS source. As this feature is visible on our Schmidt images, the emission is most probably scattered light reflected off the walls of the cavity formed by the outflow as it bores its way out of the globule. Using AAO/UKST Hα material, we have identified a similar feature associated with the cometary globule and outflow complex CG30/HH 120 (Zailey et al. 1999). The Hα streamer extends to the south–west of the globule and appears to be the optical counterpart of an extensive H2 filament associated with the infrared source CG30–IR51. The tube-like feature in Ori I–2 and the streamer in CG30 may represent limb–brightened cavities.

3.1.2 HH 444 (Figs 1 & 4)

Located in the vicinity of ζ Ori (Fig. 1), V510 Ori (= HBC 177) was first classified as a T–Tauri star based on an objective– prism survey of the Orion region by Sanduleak (1971). Cohen & Kuhi (1979) list the star as a classical T–Tauri star (cTTs) with W(Hα) > 10Å. The Hα emission–line survey of Wiramihardja et al. (1991) found the source to be
a strong Hα emitter with $V = 14.6$ mag as opposed to $V = 13.54$ mag found by Mundt & Bastian (1980).

By use of Hα material, the first optical detection of the V510 Ori jet (Parker & Phillipps 1998b; this paper) is shown in Fig. 4a. The jet has previously been identified by long-slit spectroscopic studies (Jankovics, Appenzeller & Krautter 1983; Hirth, Mundt & Solf 1997). The scanned Hα image (Fig. 7a) reveals a highly collimated jet. Several faint knots (A–C) are located 57, 84, and 194 from V510 Ori. The flow terminates at the large bow shock structure HH 444D, which displays wide wings which sweep back towards to position of V510 Ori.

The Hα+[Sii] image (Fig. 4b) clearly identifies the HH 444 jet extending from V510 Ori. Due to the seeing conditions at the time ($\sim 3$), we can only confirm the presence of knots B and D in the Hα+[Sii] image. For the continuum frame (Fig. 4c), conditions were slightly better and based on the scanned Hα and continuum image, knots A–C are considered as pure emission–line features. The jet appears as two separate parts, with the first section appearing as a dense region extending 10 from V510 Ori, while a second, more fainter part extends a further 6. This change may represent several individual condensations not resolved by our images. The total projected length of the optical flow is 0.6 pc in length.

The small separation between V510 Ori and its jet implies the jet is still active today and coupled with the fact that we do not see an obvious counter flow suggests an evolved case of a one–sided jet (Rodríguez & Reipurth 1994). High resolution optical and near–infrared studies of the jet and energy source will be beneficial in determining the nature of this unusual outflow complex.

### 3.2 New objects in L1641

As shown in Fig. 5, the northern border of L1641 is approximated by the bright ionisation front near the open cluster NGC1981. The cloud extends several degrees south of the figure. The Hα emission surrounding the bright H region M42 shows substantial substructure. The southern portion of the image is bounded by the bright reflection nebulosity NGC1999. In contrast to the L1630 region, we have identified 15 HH complexes within the outlined region shown in Fig. 5. The region is shown in more detail in Fig. 6, where the new objects and features of note are indicated. Several strings of objects appear to extend to the north and northeast of the figure. The outlined region towards the centre of Fig. 6 contains a cluster of objects surrounding the high–luminosity source IRAS 05338–0624 ($L_{\text{bol}} \sim 220 L_\odot$).

#### 3.2.1 HH 292 (Figs 6 & 7)

Located in the south–east portion of Fig. 6, BE Ori (= HBC 168; IRAS 05345-0635) is a classical T–Tauri star with $W$(Hα) $> 10 A$ (Cohen & Kuhi 1979; Strom, Margulis & Strom 1989a). No molecular outflow was detected by Leveault (1988). The near–infrared photometry of Strom et al. (1989a) indicates excess emission suggesting the presence of a remnant circumstellar disk.

In Fig. 7, our scanned Hα and CCD images clearly show a highly collimated flow originating from BE Ori. The flow has also been identified by Reipurth (1999; private communication). On the Hα scan (Fig. 7a), knots B–D appear to be linked by a stream of Hα emission which could be interpreted as a jet. BE Ori itself is surrounded by diffuse Hα emission which extends towards knot A, which is to the south–west of the source. All these features are confirmed by our Hα+[Sii] and continuum images (Figs 7b,c). All knots appear Hα–bright with knot B displaying a combination of emission and continuum emission. Designated HH 292, the flow extends along PA $= 45$ with knot A located 1147 to the south–west and knots B–D located 212, 473 and 644 to the north–east of BE Ori respectively, making the total flow length 0.4 pc. In their survey of L1641, Stanke, McCaughrean & Zinnecker (1998; hereafter SMZ98) identified compact H2 emission associated with knots A and D (SMZ 25), which may represent the terminal working surfaces of the flow where the wind is encountering dense material.

It is interesting to note the asymmetry in Hα emission with respect to BE Ori. The lack of optical counterparts to knots B–D to the south–west of the source suggests BE Ori has either undergone highly irregular outbursts in the past, or has a one–sided jet (Rodríguez & Reipurth 1994). Assuming a tangential flow velocity of 150 km s$^{-1}$, knots B–D have ages approximately 300, 700 and 1000 yr respectively, suggesting periodic outbursts every 300–400 yr whereas knot A has an age of 1700 yr. As the seeing during our observations of BE Ori was $\sim 3$, deeper imaging may reveal further Hα emission and constrain the ejection history of the source.

#### The L1641–N region

In Fig. 8, we present scanned Hα, IIIaF and IVN images of the outlined region in Fig. 6 where a cluster of faint red nebulosity was found by Reipurth (1985). The region has been mapped in $^{12}$CO by Fukui et al. (1986, 1988) who found a bipolar outflow, L1641–N, centred on the bright far–infrared source IRAS 05338–0624. Near–infrared imaging of the region by Strom et al. (1989b), Chen et al. (1993) and Hodapp & Deane (1993), revealed a dense cluster of approximately 20 members surrounding the IRAS source. Davis & Eisloeffel (1995; hereafter DE95) and SMZ98 identified a multitude of H$_2$ ($2.12\mu m$) emission which outlines a cavity bored out by the CO outflow and multiple jet and bow shock features which extend at least 2 pc to the south of the embedded cluster.

In the following, we present our CCD images of the region shown in Fig. 8 which confirm many of the Reipurth nebulosities as bona fide HH objects. Scanned Hα images for several of these objects are also presented in Parker & Phillipps (1998b). Independent CCD imaging of the region has also been presented by R98. Candidate energy sources for these flows are presented based on their location with respect to the optical and near–infrared emission (DE95, SMZ98).

#### 3.2.2 HH 301/302 (Figs 8 & 9)

Extending to the east of Fig. 8, the combined Hα+[Sii] image of these two objects (Fig. 9a) shows HH 301 consists of three bright knots (A–C) which form an U–like structure with several fainter knots (D–F) trailing to the south–
west. Likewise, HH 302 consists of one bright knot (A) with a fainter one (B) extending to the south–west. Both objects are brighter in [S\text{ii}] with faint H\alpha emission. This property is apparent from Figs 8a and 8b, where HH 301/302 are prominent on the IIIaF, but faint in the H\alpha image. R98 suggest HH 301/302 are related based on their elongation towards the L1641–N embedded cluster where the presumed driving source is located. A line of [S\text{ii}] emission can be seen to the south which mirrors the position of HH 301/302 and coincides with H\alpha emission (SMZ 17/18). The bright knot HH 298A (R98) can also be seen in Fig. 9a. Although R98 list HH 298 being 70 in extent with an east–west orientation, our H\alpha+[S\text{ii}] image shows HH 298 extends even further to the east of HH 298A with several knots which we label as HH 298 D–F. This makes the HH 298 flow 340, or 0.76 pc in length from knots A to F. It is interesting that together with HH 301/302, HH 298 produces a V–type structure with the apex pointing back towards the infrared cluster.

DE95 and SMZ98 identified a chain of H\alpha knots (I/J and SMZ 16 A/B respectively) which extend east from the embedded cluster with a morphology reminiscent of a jet. In fact, HH 298A appears directly between SMZ 16 A and B. As HH 298 and HH 301/302 contain both optical and near–infrared emission, we suggest they are tracing the walls of a cavity outlined by the V–type structure. The presence of a jet (SMZ 16A) and counterflow (HH 298A and SMZ 16B) suggests we are seeing a single outflow complex. As the jet extends directly between HH 298 and HH 301/302, we do not rule out the possibility of 3 separate flows, although we draw a comparison with the outflow source L1551–IRS5, where HH 28/29 are not located along the jet axis, but close to the walls of a cavity identified by optical, near–infrared and CO observations (see Davis et al. 1995 and references therein).

Chen et al. (1993) identified a K band source (their N23) in the direction of DE95 I/SMZ 16B which is not visible in our I band image (Fig. 9c). Based on the alignment of optical and near–infrared emission, we propose this source as the driving agent for both HH 298 and HH 301/302. Further spectroscopic studies are needed to clarify its nature.

### 3.2.3 HH 303 (Figs 8 & 10)

The HH 303 flow consists of two groupings of knots aligned along a north–south direction. The H\alpha+[S\text{ii}] image in Fig. 10a shows the northern–most group (knots A–F) outlines a bow–shock with a sheath of H\alpha emission overlaying clumpy [S\text{ii}] emission. Several more [S\text{ii}]+bright knots (I–K) extend towards the south. A fainter knot, HH 298A (R98) is seen to the south–west of knot K. However, Fig. 5 of R98 shows HH 298A at a different location to that shown in Fig. 10a. Therefore, we identify this knot as HH 303L in continuation of R98. R98 suggests HH 303L may be associated with HH 303, but deviates too much from the well defined axis and may represent a separate flow. We suggest knots I–K and L represent a remnant bow shock with the former and latter representing the eastern and western wings respectively.

At first glance, HH 303 could be interpreted as a highly collimated flow originating from the variable star V832 Ori (Fig. 10b). The optical and near–infrared photometry of this source (source N2 of Chen et al. 1993) shows a spectral energy distribution which declines rapidly for \( \lambda > 1\mu\text{m} \), suggesting a lack of circumstellar material. A comparison of our optical images with the near–infrared data of SMZ98 shows the majority of HH 303 displays both optical and H\alpha emission, thereby suggesting HH 303 is behind V832 Ori and unrelated to the star. Knots HH 303 B, F and I are coincident with the H\alpha knots SMZ 8A, 8B, and 14P respectively, with the H\alpha emission displaying bow shock morphologies which open towards the south in the direction of L1641–N.

As knots HH 303 I–K lie within the blue lobe of L1641–N, it has been suggested the CO, near–infrared and optical flows derive from a common source (Strom et al. 1989b; SMZ98; R98). Chen et al. (1993) identified a bright M band source (their N15) ~ 8 to the east of the IRAS position. Chen, Zhao & Ohashi (1995) detected this source with the VLA at 2.0mm, 7.0mm and 1.3cm, while SMZ98 identified a 10\mu\text{m} source coincident with N15 and the VLA source. As N15, the 10\mu\text{m} source and the 1.3cm source represent the same object, we follow R98 and label it as the “VLA source” which they suggest is the driving source for HH 303 and the illuminator of the reflection nebulosity seen to the north–east in our I band image (HD93; Fig. 10b).

However, it is important to mention that the L1641–N region is a highly clustered environment where identifying outflow sources requires the highest resolution possible. Anglada et al. (1998) identified two radio continuum sources, VLA2 and VLA3, which are 08 and 02 to the west and east respectively from the nominal position of the VLA source. Further observations of the region reveal a fainter source within 1 of VLA2 (Anglada 1998, private communication). The CO data of Fukui et al. (1986; 1988) clearly indicates the L1641–N molecular outflow is more complex than a simple bipolar outflow. Higher resolution studies of these sources are needed to determine which source is driving the optical and H\alpha emission. In particular, it would be interesting to see if the VLA source displays an elongated radio jet with its long axis pointing in the direction of HH 303.

In addition to HH 303, R98 suggest the VLA source also drives HH 61/62, which are located 468 (6.5 pc) to the south of L1641 (see Fig. 18). If their assumption is correct, the HH 61/62/303 flow is 7 pc in length, with the northern lobe only 5% the length of the southern lobe. Any shocks associated with the northern lobe will be extremely faint due to the lack of molecular material as the flow moves away from L1641.

### 3.2.4 HH 304 (Figs 8 & 11)

Located to north–east of the VLA source, the [S\text{ii}] image of HH 304 (Fig. 11a) shows several compact knots which are [S\text{ii}]+bright. Knot B is compact with a bow shock structure (knot A) extending towards the north–east and then curls back to the north–west. Knots C and D display an opposing bow shock structure, with knots C and D connected by faint [S\text{ii}] emission. The overall morphology of the system suggests the energy source is located between knots A/B and C/D. The I band image (Fig. 11b) shows a compact reflection nebulosity with a tail which mimics part of the [S\text{ii}] emission associated with knots A and B. A reddened source (which we
The HH 304 complex is also seen in the H₂ mosaic of SMZ298, who label it SMZ 5. HH 304A is seen as a bright bar which extends 6 along an east–west direction. At the position of the compact reflection nebulosity, a bright H₂ knot is seen, with a trail of H₂ emission extending from HH 304IRS towards HH 304C. The appearance of the optical and near–infrared emission suggests we are seeing two lobes with knots A and C representing the north–eastern and south–western working surfaces respectively. HH 304IRS appears midway between these two opposing working surfaces. There are no IRAS or Hα emission–line stars at the location of the reflection nebulosity, which implies a deeply embedded source.

**3.2.5 HH 305 (Figs 8 & 12)**

The HH 305 outflow appears aligned along a north–south axis centred on the bright (V ∼ 11.3 mag) star PR Ori. With the exception of knots A and F, all objects are Hα–bright, with knot B displaying an inverted V–type structure only visible in Hα. Knot A shows a bow shock structure which opens towards PR Ori. It is interesting to note that HH 305E represents the brightest nebulosity in the flow. The increased brightness could be attributed to the flow encountering an obstacle of some sort, perhaps in the form of a molecular clump. The dark lane seen in Figs 6, 8 and 12 represents a change in the molecular distribution in this part of L1641. At the position of HH 305E, the flow impacts the molecular cloud and then deflects to where we see HH 305F. Based on their separation from PR Ori, R98 suggest knots C/D represent an HH pair located 16 from the source. Similarly, knots B/E and A/F represent HH pairs located 65 and 108 from PR Ori respectively, making the total flow length 0.54 pc.

At present, it is unknown if HH 305 is being driven by PR Ori or a more embedded source behind it (R98). In a major study of *Einstein* X–rays in L1641, Strom et al. (1990) identified PR Ori as a low–luminosity (13 L⊙) source with a spectral type of K4e and W(Hα) = 0.5A. Their JHKL photometry indicates a lack of infrared colour excess normally attributed to a circumstellar disk. Based on their data, PR Ori appears to be a weak–lined T–Tauri star (wTTs). Its location with respect to the L1641 molecular cloud shows it lies in a region of low obscuration and in addition to the fact that SMZ98 did not detect any H₂ emission associated with HH 305 rejects the notion of an embedded, more younger source located behind PR Ori.

If PR Ori is the energy source of HH 305, it would present a major discrepancy in star formation theory as wTTs are not thought to be associated with circumstellar disks and/or outflow phenomenon. Magazzu & Martin (1994) identified what was thought to be a HH flow associated with the wTT, HV Tau. Woitas & Leinert (1998) suggested the HH object is actually a companion T–Tauri star with strong forbidden emission lines whose presence originally led Magazzu & Martin to their conclusions. How do we reconcile the fact that PR Ori is a wTT with an outflow? The answer may lie in Table 2 of Strom et al. (1990), who list PR Ori as an optical double. Our CCD images also show PR Ori as an extended source, in which case it seems more plausible the companion (PR Ori–B) is the driving source of HH 305. Clearly, further studies of this HH complex are needed.

**3.2.6 HH 306–309 (Figs 6 & 13–16)**

Figs 6 and 13 show scanned Hα and IVN images of a string of emission–line objects (HH 306–309) extending away from the VLA source and up into the main reflection nebulosity of M42. A large arcuate structure (HH 407) can be seen near the bright stars towards the western border. The large rim of Hα emission identified in Fig. 6 is seen orientated at PA = 55 and appears to surround all objects in the figure. A comparison of the Hα and IVN images confirms all objects are pure emission–line features.

**The HH flows**

In conjunction with the IVN image (Fig. 13b), our Hα+[Sii] images confirm all as bona fide HH objects. In Fig. 14, the Hα+[Sii] image shows HH 306 consists of two bright compact knots (B and F) with a trail of emission extending to the south. A further knot, HH 306G, lies to the west which may be unrelated, or part of an older fragmented shock. HH 307 consists of several bright knots which mark the apexes of large arcs or wings which sweep out and open towards L1641–N. R98 suggest HH 308 appears as a fragmented bow shock with knots A and B representing the eastern and western wings respectively. Located between HH 308A and B, we note the presence of a third knot not identified by R98 which we denote here as HH 308C. HH 309 (Fig. 15) shows a similar structure to HH 308, with knots A and B representing the first fragmented bow shock, knot C the second and knots D/E the third. The reverse bow shock morphology of HH 309B can be explained by noting the distribution of Hα emission on the scanned Hα and CCD Hα+[Sii] images. The knot appears to have curled around the background emission which may have been responsible to creating the fragmented appearance of HH 309.

In searching for further emission north of HH 309, R98 discovered several bow shock structures, designated HH 310, within the main nebulosity of M42 (see Fig. 6). The objects are brighter in [Sii] than in Hα, thus discounting the possibility they might be photo–ionised rims. We have also imaged these structures and for completeness, present our Hα, [Sii] and continuum images in Fig. 16. Our [Oiii] frame (not shown) does not detect the bow shocks associated with HH 310, thereby suggesting the flow is moving with a velocity less than 100 km s⁻¹. Our [Sii] and continuum images (Figs 16a,b) identify several bow shock structures to the north–west of HH 310 which are [Sii]–bright and absent in the continuum frame. Assuming for the moment these features are bona fide HH objects, their apparent deviation from the axis defined by HH 310 can be explained if the flow is being redirected by an obstacle, possibly the long tongue–like feature which extends from the top of the images. An alternative explanation is that they form part of a separate flow, perhaps from the L1641–N region. Spectroscopic observations of these features are needed to determine if they are HH shocks.
The embedded counterflow

To the south of L1641–N, SMZ298 discovered a long chain of bow shocks. Designated SMZ 23, the chain consists of at least 7 bow shocks (A–G) which may represent the redshifted counterflow to HH 306–310 (this paper, R98). From the $^{12}$CO data of Bally et al. (1987), the integrated moment map (Fig. 17) shows evidence of a cavity created by SMZ 23. What is interesting about this cavity is its size and orientation with respect to L1641–N, HH 306–310 and the large cavity dubbed by R98 as the “L1641–N chimney”, which they suggest has been excavated by the repeated passage of bow shocks associated with HH 306–310. The location of individual knots associated with SMZ 23 appears to trace the western wall of the southern cavity, suggesting the flow impacts with the cavity wall which produces the observed emission. We suggest this southern cavity is being excavated by SMZ 23 as the redshifted flow propagates into and away from L1641–N. The $^{13}$CO velocity structure of the southern cavity is evident from 5–8 km s$^{-1}$, with the L1641–N molecular core and the “L1641–N chimney” appearing around 8 and 8–11 km s$^{-1}$ respectively. This gives further evidence that the southern cavity and the “L1641–N chimney” represent expanding red and blueshifted lobes centred on the L1641–N chimney. Following similar arguments in R98, we find the dimensions of this southern cavity to be 5x 12 in length, giving a total area of $\sim 1 \times 10^{23}$ cm$^2$. Assuming the intensity in the cavity lies within 3–5 K/km s$^{-1}$, the total mass excavated by the SMZ23 flow is $\sim 37-62 M_\odot$. In comparison, R98 find HH 306–310 has removed $\sim 190 M_\odot$ of gas from L1641. Apart from obvious errors in estimating the $^{13}$CO intensity and cavity size, we should point out we have not taken into account the possibility the southern cavity may have been formed by the combined action of more than one outflow.

SMZ 23, HH 306–309 and HH 310 all display large bow shock structures which open towards the L1641–N region where the presumed energy source lies. As mentioned for HH 303, the high degree of clustering about the VLA source confuses identifying specific energy source(s). However, the principal components HH 306B, HH 307A, HH 308C and HH 309A are located 806, 1152, 1331, 1955 away from the position of the VLA source. In addition to HH 310A (2764), the HH 306–310 lobe is 6.3 pc in length. As the SMZ 23 flow appears to extend further south from SMZ23G (Stanke 1999; private communication), the geometry of HH 306–310 and SMZ 23 about the VLA source and VLA2/VLA3 strongly favours at least one of them as the energy source of the optical and near–infrared emission. Whichever of these sources is responsible for the observed emission, the combined length of HH 306–310 and SMZ23 lobes is 10.5 pc. High–resolution radio studies will be beneficial for identifying radio jets and their orientation with respect to the optical and near–infrared emission.

The southern L1641 region

In a search for optical counterparts to HH 306–310, our deep IIIaF plate of the southern region of L1641 identifies several features reminiscent of large bow shocks. The IIIaF image of these features is shown in Fig. 18, where object A appears as a diffuse feature and object B appears as a bright nebulosity with a long curve which extends 16 to the north near object A. At first glance, object B and HH 61/62 (the counterlobe to HH 303; R98) appear to outline the eastern and western wings of a large fragmented bow shock structure. Objects C and D appear as large arc-like structures which open to the north and are 3–4 in extent. As C and D are located well away from the main cloud, our line–of–sight increases which may suggest they are not physically associated with L1641. We should also note that many of the terminal bow shocks associated with parsec–scale HH flows show substantial substructure which is lacking from the IIIaF image. In order to resolve the nature of features C and D, we obtained Ha and [S$\alpha$] images, but due to variable cloud cover, we were not able to classify these objects as bona fide HH objects. Deeper images and/or spectra of objects A–D are required to determine if they are photo-ionised regions or HH objects.

3.2.7 HH 403–406 (Figs 6 & 19)

To the north–east of Fig. 6, a second string of objects extends away from the L1641–N cluster. HH 403 and HH 404 are located well clear of the eastern edge of the L1641 molecular cloud. Although seeing at the time of observing was > 3, our Ha and [S$\alpha$] CCD images (not shown) did allow us to classify these features as genuine HH objects. In Fig.19, the scanned Ha and IVN images show HH 403 consists of a large number of emission–line knots in addition to a curved (HH 403G) and amorphous feature (HH 403H) to the south–west. The CCD images of R98 clearly shows HH 403 as a highly fragmented object which is very similar in appearance to HH 262 (López et al. 1998). A further 9 to the north–east, HH 404 displays a sickle–like structure not too dissimilar from the HH 47 jet (Heathcote et al. 1996). As these features are Ha–bright, R98 raised the question as to whether or not HH 403/404 are bow shocks or bright rims. However, based on morphological grounds, they suggest HH 403/404 are highly fragmented bow shock structures which point back towards L1641–N where the presumed energy source lies. Our contrast–enhanced scanned Ha images of the region (Fig. 19a) appears to confirm their suspicion as we see a lack of background Ha emission in the direction of HH 403/404 which has probably been removed by the action of the flow as it propagates away from L1641.

The scanned Ha image identifies several large–scale bow shocks with HH 403 and HH 404 at their apexes. R98 do not detect these features on their CCD images. Originally thought to be bright rims, comparison of the Ha emission with the $^{13}$CO data of Bally et al. (1987), indicates these “rims” do not outline the L1641 molecular cloud, or any other well–defined $^{13}$CO ridge. The first bow shock is defined by the arc–like object HH 403G and HH 404H representing the eastern and western wings respectively. The eastern wing trails 7 to the south before it blends into the background Ha emission. The second bow shock appears as an extended feature similar in appearance to HH 403G. The third bow shock only displays the western wing which extends north–ward from the second bow to the apex of HH 404, which shows a bright arc with faint Ha emission which combine to form an inverted U–type structure.
North-east of HH 404, a faint object HH 405 displays Hα emission extending along PA = 45. R98 suggest the emission is reminiscent of a jet. A further 6 to the north-east, HH 406 is a large diffuse object. Are HH 405 and H 406 related to HH 403/404? The IVN image (Fig. 19b) shows a reddened source (denoted HH 405IRS) at the position of HH 405. A reflection nebula is also seen nearby. The position of the nearest IRAS source, 05347-0545, is shown in our IVN image. It is a 60 and 100μm source only, indicating it is heavily obscured and may be related to HH 405 and/or HH 406. Based on the location of HH 405IRS with respect to HH 405/406 and the reflection nebula, we suggest this source is the driving agent for HH 405 and HH 406 thereby making the flow length 0.78 pc in extent. Near-infrared polarimetry and imaging will be useful for determining if HH 405IRS or IRAS 05347-0545 is the illuminator of the reflection emission.

Located to the far south-west of L1641–N, R98 noted HH 127 mirrors the position of HH 404 with L1641–N positioned at the centre (see Fig. 18). Although HH 127 lies at an angle of 10 from the HH 403/404 and L1641–N axis, they suggest HH 403/404 and HH 127 represent the blue and redshifted lobes respectively of a 10.6 parsec–scale flow centred on the VLA source. Given the clustered nature of potential outflow sources about the VLA source, proper motion studies of HH 127 and HH 403/404 are highly desirable to constrain the location of their energy source(s).

### 3.2.8 HH 407 (Figs 6, 13 & 20)

Located 283 north-west of L1641–N and within close proximity to HH 306–310, Figs 6 and 13 identify a large, highly fragmented structure located in the direction of several knots C/D. Located 283 north-west of L1641–N and within close proximity to HH 306–310, Figs 6 and 13 identify a large, highly fragmented structure located in the direction of several knots C/D.

As the streamers of HH 407 point towards the L1641–N region, it seems probable the energy source lies in that direction. An examination of the H2 data of SMZ98 does not reveal any emission extended towards HH 407. After re-examining our Hα plate, we noticed the presence of a large loop–like structure (hereafter loop A) extending out of the reflection nebula NGC 1999 and in the direction of HH 407. Comparison of our scanned Hα, IIIαF and IVN images (Fig. 21) indicates loop A is a pure emission-line feature. Although faintly seen on the IIIαF image, the scanned Hα image clearly distinguishes loop A from background emission.

In a recent study of the NGC 1999 region, Corcoran & Ray (1995; hereafter CR95) discovered a second loop (hereafter loop B) of Hα emission extending west of the NGC 1999 which delineates a poorly collimated outflow associated with HH 35 and represents the counterflow to the redshifted molecular CO outflow discovered by Levreault (1988). CR95 suggest the Herbig Ae/Be star V380 Ori (which illuminates NGC 1999) drives HH 35, loop B and the molecular outflow. The presence of loops A and B suggests the presence of a quadrupole outflow in NGC 1999. Using similar arguments as CR95, we suggest loop A delineates an optical outflow which, in conjunction with HH 407, represents a 6.2 pc lobe at PA = -23 with respect to V380 Ori.

In a search for optical counterparts to HH 407, our deep IIIαF plates do not reveal any clear candidates, although if we assume loop A and HH 407 are propagating out and away from L1641, the southern counterflow may not yet have emerged from the far side of the molecular cloud. Stanke (1999; private communication) has identified a large H2 feature to the south of NGC 1999 which may represent an embedded counterflow to loop A and HH 407 (see Fig. 17).

HH 130 is a large bow shock structure located 85 south-east of NGC 1999 and has been linked to HH 1/2 (Ogura & Walsh 1992) and V380 Ori (Reipurth 1998). CR95 suggest the energy source of HH 130 is located to the north-east of knot H (see Fig. 21). If HH 130 and/or the H2 feature represents the counterflow to loop A and HH 407, the outflow axis would be bent by up to 10. A similar situation is seen in HH 127/403/404 (R98), HH 110/270 (Reipurth, Raga & Heathcote 1996) and HH 135/136 (Ogura et al. 1998). Proper motion and spectroscopic studies of HH 130, HH 407 and the H2 feature are needed to determine if their motion and radial velocities are directed away from the V380 Ori region.

Is V380 Ori the driving source of loop A? In addition to V380 Ori, CR95 found two K band sources, V380 Ori–B and V380 Ori–C, within NGC 1999. By means of speckle–interferometry, Leinert, Richichi & Hass (1997) identified V380 Ori as a binary consisting of a Herbig Ae/Be (V380 Ori) and T Tauri star. High resolution mm–interferometry of NGC 1999 will help clarify which source is driving the optical emission associated with loop A.

As shown in Fig. 17, HH 306–310, HH 407 and the f–shaped filament (Bally et al. 1987; Johnstone & Bally 1999) lie within the rim of Hα emission identified in Figs 6 and 13. Approximated by an ellipse 136 × 4 (3.6 × 0.54 pc) in size, we suggest the ellipse has formed due to the combined action of the HH 306–310 and HH 407 flows expelling molecular gas from the main cloud core. The UV radiation from the nearby bright stars excites the outer edge of the expanding molecular material which we see as the Hα ellipse. Such a large-scale movement of molecular gas by parsec–scale HH flows has been suggested for HH 34 and HH 306–310 (Bally & Devine 1994; R98).

### 4 CONCLUSIONS & FUTURE WORK

By use of a single AAO/UKST Hα film of the Orion region, we have identified emission–line nebulosities which resemble bow shocks, jets and extensive alignments of arc-shaped nebulae indicating possible giant molecular flows. Subsequent narrow and broad band CCD imaging has confirmed these features as genuine Hα objects tracing outflows ranging in size from a fraction of a parsec to over 6 pc in length. In addition to the 3 pc wide Hα rim surrounding HH 306–310 and HH 407, the Hα loop (loop A) extending out of the NGC 1999 reflection nebula have not been identified in previous studies. Although these features are faintly visible in our IIIαF images, the excellent contrast of the Hα films with respect to IIIαF and published CCD images of these regions clearly distinguishes these features from back-
ground emission, thereby allowing a thorough investigation of how outflows from young stars affect the surrounding interstellar medium. The lack of optical and molecular emission associated with HH 403/404, the presence of the Hα rim and the identification of large 13CO cavities associated with HH 34 (Bally & Devine 1994), HH 306–310 (R98) and the SMZ 23 counterflow (this paper) suggests that, in the absence of massive star formation, parsec–scale flows are the dominating factor in disrupting molecular gas in GMCs. They may also be responsible for the continuation of star formation beyond the current epoch. The creation of large–scale cavities seen in 13CO maps (R98; this paper) may produce highly compressed regions which collapse to form a new wave of star formation. In order to test this idea, high resolution sub–millimetre observations in conjunction with near–infrared H2 (2.12µm) imaging will identify and determine the distribution of newly–forming Class 0 protostars with respect to the CO cavities.

Although we have suggested candidate energy sources for many of the new HH flows, only a few (Ori I–2, BE Ori and V510 Ori) can be considered as certain. The identification of at least 4 sources within an arcminute of the VLA source warrants subarcsecond CO mapping of the region to determine which source is driving the optical and near–infrared emission associated with HH 306–310, HH 403/404, HH 407 and SMZ 23. Near–infrared spectroscopy of proposed outflow sources for HH 298/301/302, HH 304, HH 305 and HH 405 will be useful in classifying their nature for comparison with other HH energy sources. To varying degrees, the optical sources BE Ori and V510 Ori exhibit optical variability and multiple–ejection events (HH objects). The fact these sources still posses highly collimated, one–sided jets well after they have emerged from their parental molecular cloud may provide important insights into jet evolution.

In relation to the newly discovered parsec–scale flows, high resolution spectroscopy and proper motion studies of individual knots associated with HH 61/62/303, HH 306–310, HH 127/403/404, HH 407 and features A–D to the far south of L1641–N will determine velocities, excitation conditions and confirm points of origin.

Due to the success of the Orion Hα film, the Carina, Cha I/II, Sco OB1, η Oph, R CrA and CMa OB1 star–forming regions are to be surveyed in a similar fashion to that presented in this paper. The majority of these cloud complexes lie within 500 pc and maximise the detection of faint, large–scale flows for comparative studies with the Orion region where we hope to address the following questions:

- What is the nature of the energy source? Parsec–scale flows are associated with Class 0, Class I and optically–visible T–Tauri stars. Is the parsec–scale phenomenon due to inherent properties of the energy source?
- How does the flow remain collimated over such large distances? Does the nature of the surrounding environment have a collimating effect?
- To what extent do parsec–scale outflows affect star formation within molecular clouds? Is there any evidence for self–regulated star formation?

Acknowledgements

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Table 1. Plates used in the current survey.

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Table 2. New Herbig–Haro flows in Orion.

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* Independently identified by Reipurth et al. (1998).
* Source in list of Chen et al. (1993).
Figure 1. The L1630 survey region. The image was derived from an unsharp-mask print of the Hα plate. The upper north-east of the image shows the IC434 and NGC2024 HⅡ regions. Surrounding the σ Ori OB system is a diffuse shell of Hα emission in addition to numerous cometary globules and ionisation fronts which extend from NGC2024 to the open cluster NGC1981. The location of new HH flows are indicated by their numbers. North is up and east is left in all images.

Figure 2. Scanned (a) Hα and (b) IVN images of the HH 289 outflow in the Ori I–2 cometary globule. The chain of emission-line objects (1–5) are shown with respect to the embedded IRAS source (indicated by the cross). Note the bubble-like structure surrounding the eastern side of the globule.

Figure 3. (a) Combined Hα+[SⅡ] image of the HH 289 outflow showing the outer knots C–F. The inner region of the globule seen in (b) Hα+[SⅡ] and (c) H2 clearly show knots A and B have both optical and near-infrared emission. The position of the IRAS source is marked by the circle in the H2 image. The feature marked “cavity” may represent a cavity evacuated by the outflow as is propagates out of the globule.

Figure 4. (a) Scanned Hα, (b) Hα+[SⅡ] and (c) continuum images of the HH 444 outflow. The Hα and Hα+[SⅡ] images clearly show the jet from V510 Ori. The large bow shock structure, HH444D, sweeps back towards V510 Ori. Note the absence of a counterjet the the south-west.

Figure 5. Unsharp-mask Hα scan of the L1641 survey region. The northern extent of L1641 is indicated by the bright ionisation rim near the open cluster NGC1981. The bright HII region M42 (NGC1976) is surrounded by highly structured filaments with several cometary globules seen to the east. The bright reflection nebulosity NGC1999 is seen at the southern edge of the image. The box outlines the region shown in Fig. 6 where a large number of HH objects have been identified.

Figure 6. Scanned Hα image of the L1641–N region outlined in Fig. 5. The HII region M42 (NGC1976) is seen to the north-west with the reflection nebulosity NGC1999 seen to the south. New objects are numbered and indicated by a single object to avoid confusion. A large rim of Hα emission appears to surround the HH 306–309 and HH 407 group. To the north of HH 309, R98 identified several bow shocks (HH310) in the main nebulosity of M42. As a scale reference, the 3 pc flow HH34 is shown with its northern (HH33/40) and southern (HH38) terminal working surfaces. The central source (34 IRS) is indicated by the cross. The bordered region (see Fig. 8) contains a cluster of objects surrounding the bright IRAS source 05338-0624 (marked as VLA).

Figure 7. (a) Scanned Hα image of BE Ori and the HH 292 outflow. A stream of Hα emission, or jet, links three knots (B–D) to the north-east, while a further Hα knot (A) is seen to the south-west. (b) CCD Hα+[SⅡ] and (c) continuum images of HH292. HH292B comprises of both emission and continuum emission.

Figure 8. Scanned (a) Hα, (b) IIIaF and (c) IVN images of the region outlined in Fig. 6. Note that many of the nebulosities on the IIIaF are rather faint in comparison to their appearance in Hα. The indicated nebulosities are absent from the IVN image, confirming they are pure emission-line objects. The emission-line stars PR Ori and V832 Ori are indicated and the location of the VLA outflow source (IRAS 05338–0624) is indicated by the box.

Figure 9. (a) Hα+[SⅡ] and (b) I band images of the HH 298, HH301 and HH302 outflows identified from Fig. 8. The cross in the I band image marks the location of the presumed energy source (N23 of Chen et al. 1993) for HH301/302.

Figure 10. (a) Hα+[SⅡ] and (b) I band images of the HH303 complex identified from Fig. 8. The circle marks the location of the VLA source, which R98 propose as the driving source for HH303.

Figure 11. (a) [SⅡ] and (b) I band images of the HH304 outflow located in the north-east of Fig. 8. Knots A/B and C/D represent opposing bow shocks with a reddened source located at knot B. The candidate energy source (HH304IRS) displays a fan of reflection nebulosity extending to the north-east.

Figure 12. Hα+[SⅡ] image of the HH305 flow identified from Fig. 8. Knot E marks the location where the flow may be deflected by a dense region indicated by the darkened strip seen to the south of the image. Note that PR Ori appears slightly extended and is in fact an optical double, where the companion is the proposed energy source for HH305 (see text).

Figure 13. Scanned (a) Hα and (b) IVN images of the northern objects HH306–309 and HH407 identified in Fig. 6. The large rim of Hα emission is clearly visible and as no emission is seen in the IVN image, the rim is identified as a pure emission-line feature.

Figure 14. Hα+[SⅡ] image of HH306–308. In addition to several bright knots, the HH307 bow shock clearly displays larger bow shock structures which open to the south and have the bright knots at the apex of the bow. HH308 appears as a highly fragmented bow shock with HH308A displaying an elongated structure (see text for details).

Figure 15. Hα+[SⅡ] image of the HH309 bow shock. The reverse morphology of knot B can be explained as the flow passes over the background Hα emission which extends from the north-east to the south-west of the figure.

Figure 16. (a) [SⅡ] and (b) continuum images of the HH310 region (see Fig. 6 for location). To the north–west we see several "bow shocks" which may be genuine HH objects associated with HH310. They may be deflected from the flow axis by the tongue-like feature which extends from the top of the figure.
Figure 17. Integrated $^{13}$CO map of the L1641 cloud from Bally et al. (1987). The emission has been integrated from 5.4 km s$^{-1}$ to 11.4 km s$^{-1}$ with respect to the L1641–N cloud velocity (8.4 km s$^{-1}$). Filled and open circles represent the HH306–310 and SMZ 23 flows respectively. The western wall of the southern cavity is traced by the SMZ 23 flow. A H$_2$ feature (++) may represent the embedded counterflow to HH 407 (++). The VLA and V380 Ori outflow sources are indicated. The location of the H$\alpha$ rim with respect to HH 306–310 and HH 407 is indicated by the ellipse. The $\int$–shaped filament (Bally et al. 1987) is seen to the north and approximates the western wall of the “L1641–N chimney.” The wedge shows intensity in units of K/km s$^{-1}$.

Figure 18. IIIaF image of features A, B, C and D to the far south of L1641–N. To the south–west the cloud boundary is clearly seen with respect to the background star field. The features are not visible on IIIaJ and IVN plates which suggests they are emission–line objects, possibly HH objects originating from the L1641–N region. The position of the VLA source is marked by a box for reference and comparison with Fig. 6. The near–infrared counterlobe to HH 306–310, SMZ 23, is indicated by open circles. HH 61/62 are thought to be associated with HH 303, while HH 127 represents a possible counterlobe to HH 403/404 (R98).

Figure 19. Scanned (a) H$\alpha$ and (b) IVN images of the HH 403/404 and HH 405/406 complexes identified in Fig. 6. The H$\alpha$ image has been enhanced so as to show the HH 403/404 outflow has cleared away a significant portion of dust in the region as it propagates away from the L1641–N region. HH 403/404 are located at the apexes of two large bow shocks (bow 1 and bow 3 respectively). The IVN image identifies a reddened source, HH 405IRS, which has associated reflection nebulosity and is the proposed energy source for HH 405/406. The nearby IRAS source 05347–0545 may be related to HH 405/406 and/or the reflection nebulosity between it and HH 405IRS. The major and minor axes of the IRAS error ellipse have been multiplied by two for clarity.

Figure 20. H$\alpha$+[$S$ii] image of the fragmented HH 407 bow shock identified in Figs 6 and 13. Knots A and B display arcuate morphologies. Objects C and D are part of a streamer which trails several arcminutes to the south–east.

Figure 21. Scanned (a) H$\alpha$, (b) IIIaF and (c) IVN images of the NGC1999 region. The H$\alpha$ image clearly identifies two loops of emission extending out of NGC1999. HH 130 is a large arcuate object which extends from the bright bow shock HH 130A to HH 130H. The IVN image indicates the positions of V380 Ori and VLA1, which are the illuminating and driving sources of NGC 1999 and HH 1/2 respectively.