Discovery of a family of Herbig–Haro objects in M42: implications for the geometry of the high velocity molecular flow?

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Summary. We present the results of an \([\text{O} \text{I}] \lambda 6300\) electronographic survey for Herbig–Haro objects in the Orion Nebula. Six objects without continuum or infrared counterparts have been discovered close to the known high velocity HH object, M42 HH1, one of these being the closest known optical object to the BN source. High dispersion spectroscopic data reveal that the objects are characterized by the presence of high velocity blue wings in the low-excitation lines. The maximum velocities range between \(-100\) and \(-380\) km s\(^{-1}\) with respect to the ambient \([\text{O} \text{I}]\) gas.

The existence of an enhanced zero-velocity component leads to the view that the objects are stationary condensations embedded within a high velocity stellar wind. We present evidence that this wind source must be located behind the \(\text{H} \text{II}\) region within the molecular cloud, close to the BN infrared complex. Taking our results in conjunction with existing molecular line observations and the unpublished 2.2 \(\mu\)m continuum map of Hyland \textit{et al.} we argue that both the HH objects and the high velocity molecular gas are driven by a very high energy biconical stellar wind which is collimated by a dense molecular disc.

1 Introduction

Most of the known Herbig–Haro (HH) objects have been discovered using either broad band photography (Herbig 1974) or objective prism surveys (Schwartz 1979) of dark clouds. However, in regions where there is a strong emission-line background neither approach is satisfactory, and it is therefore not surprising that the list of identified HH objects contains only two which are situated in \(\text{H} \text{II}\) regions; M42 HH1, discovered during studies of the neutral oxygen emission in the Orion Nebula (Münch & Taylor 1974; Gull 1974; Münch

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1977) and the NGC 2264 group discussed by Adams, Strom & Strom (1979). The association of HH objects with the early stages of stellar evolution and the copious star formation occurring in H II regions suggest that, unless HH production is somehow inhibited, large numbers of currently undetected HH objects could exist within H II regions. The discovery of an H II region HH population would provide an opportunity to investigate the influence of protostellar winds on the evolution, energetics and dynamics of H II regions. If such a hidden HH population is to be found, an alternative survey technique, to those discussed above, is required.

The obvious alternative approach is direct imagery through narrow-band interference filters, chosen to select lines which are prominent in the shock excited HH objects (Dopita 1978) but relative weak in the surrounding photoionized H II regions. Of the strong low excitation lines in the visible, [O I] $\lambda$ 6300 is the most suited to this method since it offers better discrimination with respect to the H II region than, for example, the [S II] $\lambda$ 6717, 6731 doublet, frequently used for differentiating supernova remnants from H II regions in external galaxies (Sabbatin & Binanchini 1979) and is 6–10 times stronger than the [N I] $\lambda$ 5198, 5200 doublet in HH objects (Dopita 1978). We present here the results of a survey of M42 obtained using direct electronographic imagery in [O I] $\lambda$ 6300, H$\alpha$ $\lambda$ 6563 and the continuum. On the basis of these observations we have been able to identify seven stellar or semi-stellar [O I] condensations, all to the north of the Becklin–Neugebauer (BN) source, which we argue are clustered in a family group. High dispersion spectroscopy of these condensations show that they possess large negative velocity components ($V < 100$ km s$^{-1}$) with respect to the surrounding nebula gas and strengthen the argument that they are physically associated.

Details of the electronographic and spectroscopic observations, which provide the foundation of our case that the [O I] condensations are HH objects, are given in Sections 2 and 3 respectively. In Section 4 we discuss possible models for the origin of the new HH objects in M42, while in Section 5 we present a geometric model for the Orion Molecular Cloud which we feel explains many of the observed features of this region.

2 Electronographic results

Monochromatic images of M42 over a 20 arcmin field centred on $\theta$1 Orionis were obtained using a 40-mm McMullan electronographic camera (McMullen, Powell & Curtis 1972) mounted at the f/7.5 Cassegrain focus of the 1-m reflector at the Wise Observatory, Israel, in 1979 January and February. Since our aim was to identify features strong in [O I] relative to the dominant H II region lines we used triple period image quality interference filters at

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Plate 1. An [OI] $\lambda$6300 image of Orion. The scale and orientation are as shown. The boxed region is shown in more detail in Plate 2.
Plate 2 (a). The region of primary interest in this study. (a) [OIII] λ5007 image of the boxed region in Plate 1. (b) corresponding λ6300 continuum image. The identifications of the Herbig-Haro objects are as given in Table 2. The cross marks the position of the Becklin-Neugebauer source.
central wavelengths of λ 6303 [O I], λ 6568 (Hα) and a Gaussian shaped λ 6400 (continuum) filter with full width at half maximum band-passes of 11, 17 and 100 Å respectively. Details of the observations are given in Table 1.

Each of the electronographs was digitized on the PDS microdensitometer at KPNO, using a 16 μm square (0.5 arcsec) aperture and a 16 μm step size.

A list of candidate [O I] knots was compiled by blink comparison of the exposures in each of the bands on the Comtal TV display of the Interactive Picture Processing System (IPPS) at KPNO. Plate 1 is a reproduction of the best [O I] image (Plate 6523), after contrast enhancement on the IPPS. In order to show the whole of the region of M42 mapped in our study, the 2048 x 2048 pixel array has been compressed by only displaying every fourth element in both dimensions of the raster. The boxed area outlined in Plate 1 is the region of primary interest in this paper and is reproduced in greater detail in Plate 2(a). A direct comparison can be made between this and the red continuum (λ 6400) electronograph which is shown at the same scale and orientation in Plate 2(b).

A complex of [O I] knots and filaments, which do not have counterparts in either Plate 2(b) or the Hα exposure, is identified in Plate 2(a) following the notation of Münch (1977). Inspection of Plate 2(a) also reveals that there is a non-stellar [O I] knot at the location of the supposed HH object M42 HH2 discussed by Cantó et al. (1980), but a continuum counterpart is present in Plate 2(b). Clearly further spectroscopy of this region is necessary to confirm the identity of the source.

The two brightest [O I] objects, identified as numbers 1 and 10 on Plate 2(a), are obviously extended, though there is no real evidence in our images for the double structure of M42 HH1 suggested by Münch (1977). Both these objects are faintly visible on the continuum image most probable due to contamination by the [O I] λ 6363 line in the wings of the filter. The ‘tails’ of both HH1 and HH10 point towards the BN source (marked as a cross in Plate 2a) and indeed their approximate intersection, if extrapolated in that direction, lies within 5 arcsec of it. Furthermore M42 HH8 is very close to the projected position of the BN source and appears to be connected to M42 HH1 by a series of filaments. M42 HH9 also has a companion filament, but this is approximately orthogonal to the radius vector from the infrared source.

Astrometric data for the semi-stellar [O I] knots were obtained using the Coradograph measuring machine of the Royal Greenwich Observatory and are given in Table 2. From comparisons between our stellar measures and those of Parenago (1954) the maximum uncertainty in the position of any object is 1.5 arcsec. This rather large error is a consequence of inadequate mapping of the optical distortions within the electronographs.

On the basis of their enhanced [O I] emission with respect to the background nebula, together with proximity on the sky, and their possible relationship with the infrared complex in Orion, we regard these newly discovered objects as candidates for classification as HH objects.

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<td>-05 23 44</td>
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<td>-05 22 34</td>
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<td>M42 HH8</td>
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<td>M42 HH9</td>
<td>05 32 46.4</td>
<td>-05 23 40</td>
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</table>

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3 Spectroscopy

3.1 Observations

The work of Münch (1977) established that, in M42 HH1, Hα and the low excitation lines such as [O I] (λλ 6300, 6363), [N I] (λ 5200) and [S II] (λλ 6717, 6731) exhibit strong high velocity wings extending approximately 240 km s⁻¹ to the blue of the ambient velocity in the background nebula, but that [N II] (λλ 6548, 6583) and the higher excitation forbidden lines do not show this structure. In order to investigate if the proximity of the newly discovered objects to M42 HH1 implied that they had similar kinematic properties we obtained spectra of all of them at high enough dispersion to enable us to resolve their line profiles in detail.

Observations of all the objects, except M42 HH8, were obtained at a dispersion of 10 Å mm⁻¹ in 1979 December using the 82-cm camera of the RGO spectrograph and the Image Photon Counting System (IPCS, Boksenberg 1972) mounted at the f/7.9 focus of the 3.9-m Anglo-Australian telescope. A spectrum of M42 HH8 was obtained in 1980 October thanks to the generosity of Alec Boksenberg and Steve Briggs. The instrumental configuration was identical to that used in 1979 and a summary of the instrumental parameters for both dates is given in Table 3. The position of the slit centre was known to an accuracy of 2 arcsec for all observations. The 1979 data were obtained in conditions of poor seeing and we could not spatially resolve M42 HH1 and HH10. In addition absolute flux calibration proved unreliable because of the large uncertainties inherent with our narrow slits in the poor seeing conditions.

A sketch of the relevant region of M42 incorporating the slit positions is given in Fig. 1. The scale and orientation are the same as in Plate 2.

The spectra were flat fielded and wavelengths calibrated using the SPICA software package on the UCL STARLINK Vax, resulting in uncertainties of only 3 km s⁻¹ in the calibrated spectra. An example of the spectrum of a spatial element in the background of the nebula is shown in Fig. 2. The wavelengths and identifications of the prominent lines are as given. There is a strong line at λ 6375.4 seen in all our spectra (shown with a '?' in Fig. 2) which is almost certainly He I, λ 3187.7 seen in second order.

In Figs 3 and 4, which show the results for all the slit positions, we will be paying particular attention to the adjacent [O I] λ 6300.3 and [S II] λ 6312.1 spectral lines. The significance of this comparison is well illustrated in Fig. 3(a) and (b) where we have displayed the wavelength region covering these two lines for M42 HH1 and HH10 respectively. In the background spectrum (Fig. 2) it is clear that both [O I] and [S II] have similar symmetric profiles. However, in Fig. 3, though the [S II] line remains symmetric, [O I] exhibits a broad blue wing. This contrast in the line profile arises because [S II] is dominated by emission from the background nebula whereas [O I] is modified by high-velocity emission associated with the object. M42 HH1 and HH10 are the clearest examples

<table>
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<th>Slit position (Fig. 3)</th>
<th>Object no. (Table 1)</th>
<th>Position angle (°)</th>
<th>IPCS format</th>
<th>Velocity resolution (km s⁻¹)</th>
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of high velocity blue wings and in order to emphasize the high velocity wings for the remaining objects we have used the neighbouring [S\textsc{iii}] line as a template by scaling and shifting it with respect to the peak of the narrow component of \([\text{O}\text{i}]\). The superposition of the two lines yields a direct comparison between the velocity structure of the object and the underlying nebula. These results are given in Fig. 4(a)–(i). In Fig. 4(j) we show the result of the same process of shifting and scaling as applied to a representative background spectrum where no high velocity material is in evidence. It is apparent from Figs 3 and 4 that the high velocity blue wings seen in M42 HH1 are a characteristic feature of all the objects. In none of the objects do we see red asymmetries on the [\text{O}\text{i}] line. Several locations outside, but close to, the objects identified from the electronographs also show high velocity blue wings. Each of these has been identified in Fig. 4 by appending a letter to the number of the nearest electronographic object, e.g. M42 HH9a. In some instances we see corresponding diffuse low contrast structure in our [\text{O}\text{i}] images, in other cases there seems to be no obvious counterpart. One such example actually coincides with the BN source itself! The similarity between these features and the [\text{O}\text{i}] condensations suggests that we have serendipitously discovered a sample of fainter objects of the same type. As yet, however, there are not sufficient of these to establish if they represent the ‘tip of the iceberg’ of a more extensive high velocity [\text{O}\text{i}] population in this region of Orion.
Since the [O\text{I}] line profiles of all the objects are so reminiscent of M42 HH1 it seems very probable that they are dynamically related objects.

### 3.2 Line Profiles

If we are to understand the origin of the high velocity [O\text{I}] flow we must establish the kinematic differences between the HH objects and the gas in the surrounding nebula. This requires us to quantify the extent of the blue wings in the HH objects and determine the turbulent line width in the underlying nebula using the [S\text{III}] and [O\text{I}] lines. In order to parametrize the shape of each line we have used a non-linear least-squares model fit to the

![Figure 3](https://example.com/fig3.png)

**Figure 3.** (a) The observed profiles of M42 HH1 in [O\text{I}] λ 6300 and [S\text{III}] λ 6312. (b) Similar plot for M42 HH10. Note the blue wing on the [O\text{I}] line and the symmetry of [S\text{III}] in both diagrams.
Figure 4. (a)–(i) Show the observed [O I] profiles for the remaining objects of Table 2. To emphasize the presence of the blue wings the [S III] line has been superimposed. (j) Superposition of [O I] and [S III] from a background region, illustrating the symmetry of the profiles.
Figure 4 – continued
data with a skewed Gaussian function, designed to simulate the asymmetry of the profiles (Frazer & Suzuki 1969).

This function is defined by

\[ H = H_0 \exp \left\{ -\ln 2 \left\{ \ln \left[ 1 + 2\alpha (X - X_0)/W_{1/2} \right]/\alpha \right\}^2 \right\} \tag{1} \]

where the free variables \( H_0, X_0 \) and \( W_{1/2} \) are the peak height, centre and modified full width at half maximum of the line respectively, and \( \alpha \) is the 'skew parameter'. For \( \alpha = 0 \) this expression is indeterminate; but because

\[ \lim_{\alpha \to 0} \ln \left( 1 + \alpha X \right)/\alpha = X \]

the function has the desirable property that it is restored to the familiar symmetric Gaussian shape. The use of this function is therefore adaptive, and only carries a slight penalty due to the introduction of an extra free parameter, even when applied to symmetric line profiles. As \( \alpha \) increases the line becomes more highly skewed, negative values of \( \alpha \) producing blue-ward asymmetries and positive values of \( \alpha \) giving redward asymmetries. In practice profile fits which yielded \( |\alpha| \leq 0.03 \) (a limit deduced from the noise level in the data) were also modelled with a standard Gaussian function. In all cases the agreement was excellent. In addition, for each line we have directly measured the maximum velocities to the blue \( \Delta W_B \) and red \( \Delta W_R \) of the line centre at 'zero intensity', which we have defined formally as that flux level corresponding to the 3\( \sigma \) confidence limit from the mean underlying continuum, thus making it independent of the peak height of the line. These parameters have also been combined to give a second estimate of the degree of asymmetry of the profile by forming the asymmetric index \( A_{100} \) used by Heckman et al. (1981) and given by

\[ A_{100} = \frac{\Delta W_R - \Delta W_B}{\Delta W_R + \Delta W_B} \tag{3} \]
### Table 4. Herbig–Haro line profile parameters: skew Gaussian fit.

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<th>$\Delta W_R$ (100)</th>
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<th>[O I] $W_{1/2}$</th>
<th>$\Delta W_B$ (100)</th>
<th>$\Delta W_R$ (100)</th>
<th>$\alpha$</th>
<th>A50</th>
<th>A100</th>
<th>[S III] $W_{1/2}$</th>
<th>$\Delta W_B$ (100)</th>
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<td>(1)</td>
<td>52</td>
<td>&lt;0.03</td>
<td>0.04</td>
<td>54</td>
<td>50</td>
<td>&lt;0.03</td>
<td>54</td>
<td>50</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>50</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>HH10</td>
<td>9–16</td>
<td>51</td>
<td>380</td>
<td>$-0.17$</td>
<td>0.69</td>
<td>(0.05)</td>
<td>(1)</td>
<td>40</td>
<td>&lt;0.03</td>
<td>0.03</td>
<td>37</td>
<td>40</td>
<td>&lt;0.03</td>
<td>37</td>
<td>40</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
<td>40</td>
<td>&lt;0.03</td>
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</table>
where we have defined equation (3) so that $A_{100}$ has the same sense as used for $\alpha$ previously. A similar quantity, $A_{50}$, has also been calculated at half maximum. The results are given in Table 4, which is structured as follows: column (1) gives the object identification, column (2) its location in IPCS cross-section numbers and columns (3–14) contain $W_{1/2}$ ($\Delta W_B$, $\Delta W_R$), $\alpha$, ($A_{50}$, $A_{100}$) grouped separately for the HH objects, [O I] background and [S II] respectively. Errors on the parameters are given in brackets and are either formal 1$\sigma$ uncertainties obtained from the optimization or derived assuming Poissonian statistics. These results confirm the reality of the observed blue wings associated with the HH objects and show that the asymmetry increases dramatically near the base of the line (i.e. $A_{100}$ > $A_{50}$). In fact only M42 HHI shows a significant asymmetry at half maximum. The main limitation of this treatment is that we have not separated the contribution made by the underlying nebulosity from the object profiles. The lack of asymmetry at half maximum could therefore be indicative that the narrow core of [O I] is almost exclusively contributed by the background nebulosity, While it is obvious that this is not the case for M24 HH1, as the core flux is enhanced significantly compared to the background, the position is less clear for the other objects. Indeed, the presence of [O I] emission in the HH objects at the velocity of the nebula gas is a key issue as it provides severe constraints on allowed models for the objects.

We have attacked this problem by modelling the line profiles using two Gaussian components; the variations of the mean velocity, velocity dispersion and intensity of the different components were then analysed using rigorous statistical procedures. To derive this information we used a constrained optimization algorithm due to Gill & Murray (1974) in a similar but not identical manner to that described in Pelat & Allain (1981). In all cases except M42 HH1, excellent fits result, with residuals consistent with the 'expectation' from Poissonian noise. The use of additional Gaussian components does not therefore seem justified. For M42 HH1 the residuals indicate that a third Gaussian component might be

<table>
<thead>
<tr>
<th>Object</th>
<th>IPCS cross-section</th>
<th>$\gamma_{1/2}$</th>
<th>$\beta_{1/2}$</th>
<th>$I_N/I_B$</th>
<th>$I_N/I_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH1</td>
<td>10–17</td>
<td>66</td>
<td>221</td>
<td>0.77</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>(0.5)</td>
<td>(10)</td>
<td>(0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH5a</td>
<td>17–22</td>
<td>63</td>
<td>138</td>
<td>2.56</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>(0.4)</td>
<td>(5)</td>
<td>(0.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH5</td>
<td>26–28</td>
<td>62</td>
<td>72</td>
<td>7.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.4)</td>
<td>(4)</td>
<td>(0.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH6</td>
<td>18–22</td>
<td>62</td>
<td>81</td>
<td>3.45</td>
<td>0.35</td>
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<tr>
<td></td>
<td>(0.5)</td>
<td>(5)</td>
<td>(0.11)</td>
<td></td>
<td></td>
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<tr>
<td>HH7</td>
<td>10–14</td>
<td>65</td>
<td>112</td>
<td>3.45</td>
<td></td>
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<tr>
<td></td>
<td>(0.5)</td>
<td>(8)</td>
<td>(0.09)</td>
<td></td>
<td></td>
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<tr>
<td>HH8</td>
<td>22–28</td>
<td>35</td>
<td>184</td>
<td>2.94</td>
<td>0.71</td>
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<td></td>
<td>(0.3)</td>
<td>(22)</td>
<td></td>
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<tr>
<td>HH8a</td>
<td>12–17</td>
<td>35</td>
<td>203</td>
<td>1.67</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>(0.3)</td>
<td>(6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH8b</td>
<td>4–8</td>
<td>34</td>
<td>124</td>
<td>3.03</td>
<td>0.89</td>
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<tr>
<td></td>
<td>(0.3)</td>
<td>(8)</td>
<td>(0.03)</td>
<td></td>
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<tr>
<td>HH9</td>
<td>12–16</td>
<td>60</td>
<td>115</td>
<td>3.70</td>
<td>1.78</td>
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<tr>
<td></td>
<td>(0.5)</td>
<td>(9)</td>
<td>(0.05)</td>
<td></td>
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<tr>
<td>HH9a</td>
<td>1–4</td>
<td>60</td>
<td>145</td>
<td>5.00</td>
<td>1.33</td>
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<td>(0.4)</td>
<td>(13)</td>
<td>(0.05)</td>
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</tr>
<tr>
<td>HH10</td>
<td>9–16</td>
<td>50</td>
<td>297</td>
<td>1.11</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>(0.5)</td>
<td>(10)</td>
<td>(0.15)</td>
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Table 5. Herbig–Haro line profile parameters: two Gaussian decomposition.
necessary to actually match the velocity profile in the middle region, but even here a satisfactory reduced \( \chi^2 \) was obtained. In each case an extensive search of feasibility space, including the use of constraints, in an attempt to force convergence to a different location, failed to yield other physically acceptable and yet statistically distinct solutions.

Table 5 gives a summary of the best fit parameters for the two components for each of the spatially summed HH objects. Here \( N_{v/2} \) and \( B_{v/2} \) are the FWHM of the core and high velocity components respectively and \( I_N/I_B \) is the ratio of their fluxes uncorrected for the emission in the background nebula. Anticipating the results of the statistical analysis, column 6 gives the ratio corrected for the contribution to the zero velocity component from the background \( I_N/I_B \).

3.3 Statistical Analysis

To avoid spurious conclusions regarding the line widths caused either by variations in intrinsic widths from region or by the variable slit widths used, we have adopted a 'matched-pairs' analysis scheme, whereby significance tests are based on differences between the HH objects and background (control) parameters for each long slit spectrum separately (Siegel 1956). Cautiously we have applied both parametric (\( t \)-test, Kendall & Stuart 1973) and a variety of robust distribution-free (non-parametric, henceforth NP) tests, in particular Wilcoxon's rank sum test (Siegel 1956). Most of the analysis was based on Tables 4 and 5, however, in investigating the intensity information we also treated each cross-section as an independent entity so that we could again use a matched pairs scheme.

Several important results emerge from this analysis:

1. The blueward asymmetries in the HH line profiles are not accompanied by a net blueshift in the peak of the core component relative to the systemic velocity of \([O I]\) in the background nebula at any meaningful confidence level (\( \beta > 90 \) per cent) for both parametric and NP tests ([O I] is everywhere redshifted by 10 km s\(^{-1}\) relative to [S III]).

2. The FWHM of the core component is not statistically different from that of the background [O I] at the 95 per cent (NP) and 99 per cent (parametric) confidence levels.

3. [O I] in the background is broader than [S III] at the 94 per cent (NP) level but not at the 99 per cent (parametric) level.

4. The objects M42 HH1, 5, 8, 8a, 8b, 9a and 10 have significantly enhanced zero component fluxes compared to the background at the 94 per cent (NP) and 99 per cent (parametric) significance levels.

5. There is no significant enhancement of the zero component in M42 HH7 and HH5a at the 90 per cent confidence limit.

These results suggest that the core component is enhanced in most of the objects and yet it has the same mean velocity and line width as the [O I] gas in the nebula, strongly implying that there is [O I] gas associated with the HH objects which cannot be dynamically distinguished from the general [O I] gas in Orion.

4. The excitation of HH objects by stellar winds

4.1 Mass Loss Mechanisms

The observations and statistical analysis presented above clearly pose a number of important questions relating to the nature of the [O I] knots in the Orion H II region which may be relevant to Herbig–Haro objects in general. Principal among these is whether all the objects
are physically associated in the sense of being excited by the same protostar or protostellar complex (as we have implied by calling them a 'family' of HH objects), or whether they all possess their own energy source.

Leaving aside this question for the moment, it now seems clear that the basic mechanism responsible for the characteristic spectra of HH objects is collisional excitation produced by some form of mass loss associated with a protostellar source. What form this mass loss takes has yet to be established.

There are three basic suggestions:

1) **Protostellar bullets:** Here each [O I] knot is thought of as a high velocity condensation or 'bullet' (Norman & Silk 1980; Chevalier 1980) created initially from instabilities in the cocoons surrounding young protostellar objects (Kahn 1974) and driven away from the environment of the protostar through acceleration by stellar wind interaction. Norman & Silk present an extensive discussion of the physics of clumpy molecular condensations in the vicinity of protostellar winds, but it remains unclear whether the clumps will remain stable for a sufficiently long time to become optical objects and whether high enough velocities can be achieved.

2) **Stellar winds:** In the view strongly advocated by Schwartz & Dopita (1980, and references therein), HH knots are thought to be neutral condensations approximately stationary with respect to the ambient gas, but strongly shocked by interactions with a high velocity stellar wind.

The predictions of this model are in substantial agreement with the observed spectra of HH objects in that it can account for the large range of excitation species observed. Furthermore, without recourse to large mass flow rates it is readily able to produce emission with a velocity approaching that of the wind, from the trailing edges of bow shocks formed around the globule.

This model will invariably lead to observed velocities substantially less than the wind velocity, since the emission-line regions will be predominantly located within the shocked region surrounding the stationary condensation.

3) **Protostellar wind cavities:** To overcome the stellar wind energetics problem Cantó & Rodriguez (1980) have developed models of the interaction of protostellar winds in conditions where the surrounding ambient unshocked gas has a strong density gradient. This is likely to be the case at the edges of molecular clouds where the most intense star formation can be expected to occur (Elmegreen & Lada 1977). Here the stellar wind cavity becomes ovoid in shape and the streaming motions along the shock front interface, away from the protostar and in the direction of decreasing ambient density, can be as high as 0.6 of the protostellar wind velocity itself. Condensations within this flow will possess both the characteristic shock excited spectra of HH objects and the high velocities associated with the wind.

### 4.2 The Location of the Stellar Wind Source

The fact that we see exclusively blueshifted asymmetries to the [O I] lines has a strong implication regarding the location of the stellar wind source(s). Clearly, if the material streaming away from the power source is in anyway symmetrically distributed, the source itself must be substantially obscured at optical wavelengths, so that the material travelling away from us buries deeper into the obscuring material and hence becomes more difficult to detect. Furthermore, Münch & Taylor (1974) showed that the systemic [O I] velocity of the Orion Nebula was redshifted by 10 km s\(^{-1}\) relative to the bulk of the ionized gas, leading to the view that the ionization front, within which the [O I] is resident, is behind the H\(\text{II}\)
region (Zuckerman 1973). For these reasons visible sources of stellar wind, such as the members of the Trapezium, are a highly unlikely cause of the high velocity material.

These arguments suggest then that the origin of the stellar wind is embedded within the Orion Molecular Cloud. Energetic considerations of protostellar winds and the observed separations between HH objects and protostars in dark clouds necessitate that the source be within 0.1–0.5 pc of the HH objects. Even though the maximum separation of our \([\text{O} \text{I}]\) knots from the BN complex is \(\sim 0.3\) pc it is natural to ask whether there are other obscured sources in closer proximity to the knots.

The unpublished 2 arcsec spatial resolution 2.2-\(\mu\)m map of the BN complex (Hyland et al. 1983) shows no evidence for point sources associated more closely with our \([\text{O} \text{I}]\) knots, down to a limiting magnitude of \(K = 13.5\). We take this result to imply both that the \([\text{O} \text{I}]\) knots do not each have their own stellar wind source, and that the origin of the flow is most probably located in the central infrared complex of Orion.

4.3 Dynamical Models

Wherever the protostellar wind source is located and irrespective of the detailed excitation mechanisms involved, a strict lower limit to the wind velocity must be given by the maximum velocity observed in the blueshifted \([\text{O} \text{I}]\) lines. This immediately implies wind velocities well in excess of 400 km s\(^{-1}\). Remembering that the observed velocities are likely to be reduced by projection effects, values of 1000 km s\(^{-1}\) are perfectly reasonable, especially when inefficiencies in transferring stellar wind energy into kinetic motions of condensation are taken into consideration. A problem, therefore, for all shock models is to determine the ambient condition in the environment of such a strong shock velocity which nevertheless produces an ultra-low excitation spectrum with lines having an ionization potential above \(S^*\) showing no signs of high-velocity emission. Another important issue in the discussion of driving mechanisms is our result that all but two of the \([\text{O} \text{I}]\) knots exhibit a narrow-line velocity component which is associated with the HH objects themselves, but, is always at the systemic velocity of the background \([\text{O} \text{I}]\) nebula. Furthermore the width of this ‘intrinsic’ zero-velocity component is identical to that of the background.

The Norman & Silk bullets would be expected to produce a substantial flux in at least the \([\text{O} \text{I}]\) line at discrete velocities identified with the motions of the bullets. To explain the zero-velocity component we would have to suppose that the bullets are neutral condensations flowing through the ambient \(\text{H II}\) gas and then the \([\text{O} \text{I}]\) emission we see is emitted primarily from the trailing edges of the bow shock formed in their wake. However, it would seem unreasonable to expect, in these circumstances, that a substantial fraction of the flux was not only at the systemic velocity of the \([\text{O} \text{I}]\) nebula but also exhibited an identical turbulent broadening to that of the background. Since our spectroscopic observations were of objects chosen on the basis of their enhanced \([\text{O} \text{I}]\) flux with respect to the background \([\text{O} \text{I}]\) emission, the fact that we see the majority of the objects with a strong zero-velocity component could conceivably be a selection effect, though it appears that even the ‘serendipitous’ objects share this property. The bullet model cannot therefore be dismissed entirely but this problem taken in conjunction with the worries about the acceleration and lifetime of the bullets puts a severe strain on the credibility of the mechanism.

For the Cantó & Rodriguez cavity model parallel arguments to these would have to be used since implicit in their model is the notion that condensations within the shock interface are moving at a velocity close to that of the wind.

If we now consider the implications of the Schwartz–Dopita model of a condensation, stationary with respect to the ambient \([\text{O} \text{I}]\) gas but being heavily shocked by impact with a high-velocity stellar wind, we may well be able to identify the ‘intrinsic’ zero component of
the [O\textsc{i}] line as emanating from the neutral regions at the shocked surface of the stationary condensation. The high velocity blue wings would then be the result of more diffuse material at the edge of the condensation being stripped from its surface due to turbulent mixing, and then being carried away by the impact of the stellar wind. Provided this material is still in neutral form, shocks propagating into these fragments will give rise to low-excitation emission at a velocity approaching that of the stellar wind. As Dopita (private communication) has suggested, the reason for a lack of high excitation emission is presumably that the emissivity of such a flow declines rapidly with rising electron temperature, away from the neutral fragments. On the basis of the foregoing discussion the most viable dynamical model appears to be one in which the high velocity [O\textsc{i}] knots are embedded within the ionization transition zone and are being struck by an energetic protostellar wind from somewhere in the vicinity of the central infrared complex.

5 A bipolar outflow model?

Intense emission from a variety of molecules is observed in the vicinity of the BN complex over a large range of velocities: Low velocity SO, SiO and OH masers (Genzel et al. 1979; Hansen & Johnston 1980), high and low velocity H$_2$O masers (Genzel et al. 1981; Downes & Genzel 1980), thermal CO and NH$_3$ emission (Knapp et al. 1981; Morris, Palmer & Zuckerman 1980), and an extensive region of 2.2\,\mu m emission from the H$_2$ molecule (Nadeau, Geballe & Neugebauer 1982, hereafter NGN; Scoville et al. 1982).

Detailed studies of the high velocity components of this gas clearly point to mass outflow from the BN complex as the cause of the motion (e.g. Kuiper, Zuckerman & Rodriguez-Kuiper 1981), a picture which corresponds very closely with our view of the HH objects. Our intention here is to discuss the relationship between the HH objects and the morphology and dynamics of this molecular gas. In particular we will present convincing arguments that both are driven by a bipolar stellar wind which originates close to BN/IRC2, and that this wind is collimated by a dense disc of molecular gas and dust. This geometrical configuration is directly analogous to those that have been recently advocated for HH objects situated in dark clouds which also show high velocity molecular clouds (Cohen 1982, and references therein).

5.1 The Geometry of the Outflow

We envisage a situation in which the flow is basically biconical, with its centre in the BN complex, the axis of symmetry of the cones being tilted out of the plane of the sky so that it is directed towards the front of the nebula in the north-west and back into the molecular cloud to the SE. The major pieces of evidence which point to this geometry are:

(a) The distribution of the 2\,\mu m H$_2$ emission is not spherically symmetric, but is elongated an axis running north-west to south-west through the BN complex (NGN 1982). Furthermore the intensity of the emission is brighter to the north-west and south-east of BN than within 10 arcsec of the source with the north-west emission having the stronger and more extensive emission (cf. NGN, fig. 3).

The H$_2$ velocity field is characterized by high velocity blue wings ($0 > V > -120$ km s$^{-1}$) with the maximum velocities occurring to the north of BN near IRC9. These blue asymmetries are very reminiscent of those of the HH objects (cf. HH1 and fig. 4 of NGN). In fact for those HH objects actually seen in projection on to the H$_2$ emission region their velocities are very similar (e.g. HH8 $V \sim -120$ to $-180$ km s$^{-1}$). As with the HH objects the H$_2$ line profiles suggest that the gas flow is directed towards us. The presence of more intense
narrow H₂ emission marking the boundary of the high velocity flow and centred at \( V_{\text{LSR}} = 0 \) for the molecular cloud is another important feature whose significance we shall return to shortly.

(b) The so called ‘plateau’ gas originating from thermal molecular lines also shows a large range of velocities \(-95 < V < +65 \text{ km s}^{-1}\) (Solomon, Huguerin & Scoville 1981; G. Knapp, unpublished but reported in NGN). The CO gas is the most extensive, covering an area \( \sim 40 \text{ arcsec} \) centred on the BN cluster (e.g. Knapp et al. 1981). The early observations did not resolve the shape of the CO plateau gas and though the profiles were broad \( (V \sim 100 \text{ km s}^{-1} \text{ FWZI}) \) they appeared symmetric (Zuckerman, Kuiper & Kuiper 1976; Kwan & Scoville 1976). Phillips, White & Watt (1982) presented evidence that the CO line profiles are asymmetric and that the sense of asymmetry changes from red to blue along an approximately south-east to north-west axis. New high resolution observations by Erickson et al. (1982) have not only confirmed the presence of asymmetries but show that the high velocity component \( (|V| > 25 \text{ km s}^{-1}) \) is bipolar in distribution along the south-east to north-west axis.

(c) High velocity H₂O masers \((|V| > 28 \text{ km s}^{-1})\) have been found in the region of the high velocity H₂ emission (Genzel et al. 1981), (the velocities of the masers increasing away from IRC2). The large proper motions of these sources and the low velocity H₂O masers in the region are consistent with expansion from a single centre within \( \pm 5 \text{ arcsec} \) of IRC2 (Genzel et al. 1981).

The picture of a high velocity bipolar outflow, centred within the BN complex, directed preferentially along a north-west to south-east axis, and confined to an angular region consistent with the sector containing the HH objects, is clearly supported by these observations. Since only material ejected towards us will eventually emerge from the molecular cloud and penetrate into the HII region, forming optically detectable objects, the negative radial velocities measured for all the HH objects, and their approximate confinement to a \( \sim 45^\circ \) sector north-west of the BN cluster, imply the the north-west sector is approaching.

If the ambient cloud density is much greater than in the flow region it will act rather like a ‘sponge’ and the impact of the wind will tend to produce excited gas with a low velocity, close to that of the molecular cloud. The general pattern of the H₂ velocity field can therefore be reproduced by interpreting the high velocity emission as originating in material associated with the wind and the narrow intense peripheral emission occurring at the interface between the stellar wind and the dense stationary ambient gas. This model can also

Figure 5. A comparison between the angular distributions of the different kinematic components and the proposed model geometry. The distributions of the low velocity gas (a) and the high velocity gas (b) are shown separately. In both figures the locations and identifications of the principal infrared sources as given by Downes et al. (1981) are shown as open circles, and the HH objects, marked as hatched dots, from Table 2. The dot dashed circle of diameter 40 arcsec represents the approximate extent of the CO plateau gas in accordance with Solomon et al. (1981). In (a) the open triangle in the location of the SiO maser and the solid triangles are the low velocity H₂O masers of Genzel et al. (1981). Where shown the attached arrows give the sense of proper motion of the H₂O masers (Genzel et al. (1981). The approximate distribution of the NH₃ emission is plotted as a solid ellipse and the cross hatched ellipses mark the ‘hot core’ regions in accordance with Fig. 3 of Genzel & Downes (1981). In addition we have also outlined the dark lane from the map of Hyland et al. (1982) with dashed lines. In (b) the positions of the high velocity \((|V| > 28 \text{ km s}^{-1})\) masers are plotted as crosses and the envelope of the high-velocity H₂ emission is enclosed in solid lines. (c) sketches the proposed model geometry. The high-velocity wind is confined to a biconical flow by a dense disc of dust and gas which is associated with the dark lane south of the BN object. The axis of the disc is tilted out of the plane of the sky so that the north-west cone is approaching while the south-east cone is receding. The low velocity gas features are attributed to the region of projection of the dense disc.
explain two other fundamental features of the anisotropy of the ejected gas, provided the density of the molecular cloud decreases towards us. Material streaming in the south-east direction cannot travel as far as that to the north-west before it runs into gas dense enough to stop it; furthermore, by virtue of its greater depth in the cloud, the line-of-sight obscuration will be increased leading to a diminished intensity relative to the gas in the north-west. Rodriguez et al. (1980) and Norman & Silk (1980) have suggested that H$_2$O masers might be dense condensations ejected from protostellar objects. While this is not inconsistent with our model we find it more appealing to suggest that the masers are in fact dense regions in the ‘walls’ surrounding the wind, thereby allowing both positive and negative velocities depending on the inclination and opening angle of the cone.

5.2 Evidence for a Collimating Molecular Disc

If the gas does flow out in a biconical geometry we must ask ourselves what constrains it to do so? The answer to this question is in our view indicated by the dichotomy between the high and low velocity molecular gas distributions close to the BN complex. To aid our discussion of this point we have plotted the distributions of the low and high ($|V| > 28$ km s$^{-1}$) velocity features on two separate diagrams; Fig. 5(a) and (b) respectively. Whereas the high-velocity gas is distributed mainly along a north-west to south-east axis as we have just described, there is a suspicion that the low-velocity features are concentrated in the perpendicular direction. Such a configuration is exactly what would be expected if a dense molecular disc were collimating the outflow along its poles. In our view, however, the most convincing evidence for the existence of such a disc is contained in the new 2.2 μm continuum map of Hyland et al. (1983). Immediately to the south of BN there is an irregular dark band running north-east to south-west across IRC2, 3 and 4 (i.e. orthogonal to the axis of symmetry of the outflow and in the ‘pinch’ of the bipolar structure). There is direct evidence that this is a consequence of increased extinction as both IRC3 and 4 have deeper 3.1 μm ice and 9.7 μm silicate absorption features than BN (Aitken et al. 1981). Increased obscuration at other locations in the dark band is also suggested by the unpublished 3.1 μm ice feature observations of Allen (private communication). We therefore propose that this dark lane is a result of viewing a dense molecular disc approximately edge-on, which occults the radiation from material behind it and is responsible for collimating the outflow. The location of the dark lane on top of the densest part of the low velocity molecular ridge (Genzel & Downes 1981) gives further weight to this interpretation and the doughnut-like appearance of the NH$_3$ hot core emission would be a natural consequence of limb brightening of a ring viewed edge on. The fact that CO is seen in absorption in this region (Hall et al. 1978) is further evidence that there is an intervening ridge of material between us and the wind source(s). The proposed model geometry is sketched in Fig. 5(c).

In this interpretation the 18 km s$^{-1}$ component would then be associated with the expansion of the disc caused by its interaction with the stellar wind, and IRC3 and 4 would be dense patches in the disc heated by the impact of the wind.

There is one final feature visible on the 2.2 μm map of Hyland et al. (1983) which we believe is additional evidence to support our model. Extending to the north-east from BN to at least IRC9 is a high surface brightness ‘fan’ structure, and though this is coincident with the region of the high velocity H$_2$ flow only ~20 per cent of the observed flux can originate in the lines. By analogy with classical bipolar nebula we suggest that this is a reflection nebulosity illuminated by the protostellar wind source. As would be expected if this interpretation is correct, large polarizations have been observed in this region at 2.2 μm (Johnson et al. 1981) and 3.8 μm (Capps, Dinerstein & Werner 1980) though they have previously
been interpreted as due to presence of aligned interstellar grains. The presence of a reflection nebulosity in the lobes of the flow is rather important as high spatial resolution polarimetry should reveal a centre-symmetric polarization pattern surrounding the molecular collimating disc, and allow an accurate determination of the position of the illuminating source, as in the archetypical examples of this behaviour R Mon (Gething et al. 1982) and S106 (Perkins, King & Scarrott 1982) and the galaxy M82 (Bingham et al. 1976). This model may allow us to overcome one of the major physical difficulties associated with the high-velocity molecular gas, the paradox of the low dissociation velocity for $H_2$ ($\sim 28$ km s$^{-1}$) and the presence of line emission at four times this velocity, if the $H_2$ emission is actually scattered by high velocity dust moving within the wind. If this is the correct explanation then the $H_2$ molecular line should also be observed to be polarized.

The idea that an energetic bipolar flow is driving the molecular motions has been gathering impetus for some time; however, the major new implications provided by our results are that the range of the wind is considerably further than supposed on the basis of the molecular observations, and that it must have an order of magnitude larger velocity than suggested by the molecular motions. Our interpretation of the cause of this activity, in particular the presence of a dense collimating molecular disc, is a radical revision of previous ideas about the conditions close to the Orion protostellar objects and may have far-reaching consequences for other protostellar sources. We eagerly await high resolution molecular observations which will verify the presence of this molecular disc.

6 Conclusions

1. We have discovered an extensive family of HH objects associated with M42 HH1 to the north-west of the BN infrared complex in Orion.

2. All the objects possess high velocity blue wings of up to a velocity of $-400$ km s$^{-1}$ with respect to the [O I] ambient gas, implying stellar winds of at least this magnitude.

3. The objects are most likely excited by a collimated protostellar wind originating from a source within the BN complex which is hidden from our view by an optically thick obscuring molecular disc. However, the HH objects themselves see directly to the exciting source down the collimated cone.

4. The same highly energetic wind is responsible for the high-velocity molecular gas.

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Herbig-Haro objects in M42