Herbig Haro Objects in the Orion Nebula[1]

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ABSTRACT

We have used the Hubble Space Telescope to image two regions of the Orion Nebula in low and high ionization emission lines. There appear to be two main systems of Herbig Haro objects in the Orion nebula – a 'North' System is centered slightly north of the BN and IRc2 sources, and a 'South' System centered south of the Trapezium stars. The North System appears to be the result of shocks on the near side of OMC-1, the host molecular cloud for M42. The sources of these HH objects is most likely to be instabilities in shocks driven by massive star winds penetrating into a region of decreasing ambient density. HH 201 displays many of the characteristics of the North System members but lacks a trailing H_2 finger. HH 208 and 209 share this latter property and also display a very different morphological form, which puts their association with the North System in doubt. The South System contains large shocks with a variety of morphologies. This system is most likely a combination of shocks in the ionized nebular gas and lower ionization shocks formed when jets from low mass young stars strike the neutral lid lying on the near side of M42.

Both shocks and photoionization affect the line excitation of HH objects in M 42, especially among the South System, where ultraviolet light from θ^1C Ori penetrates into the back side of a bow shock that moves toward the observer. Among the bow-shaped objects along the fingers in the North system, the highest excitation lines occur near the apices of the bows, as predicted by theory. Objects that lie closer to the Trapezium are more difficult to analyze because of stronger nebular emission, rendering the HH objects best visible in [O I] and [S II] emission.

Subject headings: ISM:jets and outflows–nebulae:individual (Orion)

1. Background and Introduction

Studies of stellar jets have focussed primarily on the simplest systems, those flows which emanate from single, relatively isolated low mass stars. However, multiple flows are common even among the brightest and best studied regions (*e.g* HH 1, Reipurth *et al.* 1993; HL Tau, Mundt *et al.* 1990; HH 111, Gredel & Reipurth 1993), and we can expect even greater source confusion within the clusters of giant molecular clouds if every accretion disk around a young star drives a jet. The mixture of photoionized and shocked gas also makes it more difficult to interpret emission lines from jets within H II regions; for example, emission lines formed as a shock moves through ionized gas closely resemble those from a higher velocity shock in neutral gas (Cox & Raymond 1985).

In spite of the above complications, enough is now understood about the line excitation in stellar jets to enable us to study these flows in more complex environments. Extending the study of stellar jets to dense clusters and H II regions is the the only way to understand how a typical young star interacts with its environment, because most of the stars in our Galaxy, including all massive stars, begin their lives in clusters deep within giant molecular clouds. Understanding line ratios in H II regions also requires that we distinguish shocked gas from photoionized gas before we measure canonical abundances, temperatures and densities of the H II region.

At a distance of 430 pc (Warren & Hesser 1977), the OMC-1 cloud and the Orion Nebula (M 42; NGC 1976) are the the nearest giant molecular cloud and H II region to the Sun, respectively. On the near side of OMC-1 lies a grouping of $\gtrsim 700$ stars known as the Trapezium Cluster (Herbig & Terndrup 1988, Prosser *et al.* 1994, Zinnecker *et al.* 1993), while $\sim 1'$ to the NW of the Trapezium a cluster of young stars embedded deeply within the cloud appear as infrared sources. The hottest star in the Trapezium cluster, θ^1C Ori, dominates the photoionization of the surrounding gas and produces a thin blister of photoionized material that is the famous Orion Nebula. The Trapezium lies in a zone of low gas density and is bounded on the near side by an irregular "lid" of neutral (H I) gas. This lid was originally detected by study of the 21 cm line in absorption against the nebula's radio continuum (van der Werf & Goss 1989, 1990) and we now know that the irregularities in the lid produce the patchy extinction seen across the face of the nebula (O'Dell *et al.* 1992) and the multiple low ionization interstellar absorption lines seen in the brightest stars (O'Dell *et al.* 1993).

Because the Trapezium cluster contains so many young stars, it is not surprising that many HH objects exist within the Orion nebula. The basic geometry in the Orion nebula is understood quite well (O'Dell & Wen 1992, Wen & O'Dell 1995). Shocks in outflows from Trapezium Cluster stars should occur either (1) within the low density highly ionized gas near the hottest stars, (2) within the main ionization front, or (3) in the neutral lid. HH objects driven by infrared sources within the OMC-1 cloud to the NW of the Trapezium will be heavily reddened, so optically visible shocks in this region will form preferentially in or near the photodissociation region (PDR) that lies beyond the ionized surface material.

As observational techniques have improved, astronomers have continued to discover more HH objects in the Orion Nebula. The first HH objects discovered in this region, HH 203 and HH 204 near θ^2A Ori were seen in projection against a low surface brightness part of the nebula (Munch & Wilson 1962, Taylor & Munch 1978). Munch & Taylor (1974) found HH 201 in an [O I] study while Cantó *et al.* (1980) found HH 202 in a similar search in [N II] and [S II]. A subsequent [O I] search by Axon & Taylor (1984), Taylor *et al.* (1986) added six more objects in the northern part of M42 (HH 205 – 210). A recent spectroscopic and imaging study has led to the addition of another object, HH 269 (Walter *et al.* 1995), to the southwest of the Trapezium. Infrared observations by Allen & Burton (1993; hereafter A&B) first showed clearly a unified outer structure of "fingers" of

H_2 emission, most of which had known optical HH objects at their tips. A similar structure was actually seen in the early images of Taylor *et al.* 1984 and this work has been further extended in later studies in H_2 (Schild *et al.* 1996; McCaughrean & MacLow 1996).

The paradigm that we will use for discussion of individual HH objects is that they are all shocked gas whose energy and velocity arises from material flowing from a young star. The shocked gas is compressed to higher density and raised to a high electron temperature and increased ionization while material behind this advancing shock front cools and recombines toward lower ionization, producing an ionization stratification that allows us to estimate the shock velocity and preshock density (*e.g.* Morse *et al.* 1993a).

This paper analyzes HST images of two regions of the Orion Nebula already known to contain HH objects. We first present the new observational results and show how they reveal that the known HH objects are but the brightest and best defined of a large number of related objects. We then discuss the physics of the brightest HH objects, and conclude with a discussion of the sources that drive and create M42's HH objects. There are many high ionization shock structures in the highly ionized central region near the Trapezium which manifest themselves best in [O III] (Castañeda 1988, O'Dell *et al.* 1993b, O'Dell & Wen 1994) but we will treat these in a future paper that discusses HST observations and correlated groundbased spectroscopy. Whenever possible, we will refer to the objects by their numbers in the unified designation system of Reipurth (1995).

2. Observations and Data Reduction

We observed two fields with the WFPC2 of the HST, a northern portion on 3 October 1995 and a southern on 14 November 1995 as part of General Observer program GO 5976. The filters employed were f673n to isolate the [S II] doublet at 6717+6731 Å and the f631n to isolate the [O I] line at 6300 Å. The northern field was determined by the need to fit all of the known northern HH objects into one pointing and the southern was made as a duplicate of an earlier set of images. The central intersection of the irregular WFPC2 northern field was at 5:35:13.0 −5:22:48 (J2000) with a position angle of the SE boundary of 43° and the center of the high resolution PC portion of the southern field was at 5:35:22.0 −5:25:09 with a $PA = 0°$ orientation. The full northern field is shown in Figure 1.

Both fields had been previously covered with WFPC2 images in [O III] at 5007 Å, H I Hα at 6563 Å, [N II] at 6583 Å, and the continuum at 5470 Å (O'Dell & Wong 1996). In addition, we made use of the A&B images in H_2 at 2.122 μm, [FeII] at 1.644 μm, and the J bandpass. The infrared images were made in two parts, a higher resolution ($0.26''$/pixel) coverage of the northern field and a lower ($0.61''$/pixel) coverage of the entire region. The infrared line filters used were about 1% of the wavelength, which means that that they also pass a significant amount of scattered light continuum in selected regions. The two infrared images were merged into a single image before comparison with the HST observations.

Each new WFPC2 image was actually a triple exposure, to allow adequate cosmic ray correction. The first steps of data reduction were straightforward, using IRAF[2] and STSDAS tasks to do cosmic ray cleaning, flat field correction, and integrating the four individual WFPC2 CCD images into a single mosaic. Irregularities at the seams of the CCDs were cleaned using IRAF tasks. We also made use of WFPC2 images in the same filters which were obtained as parallel observations during program GO 5469 of John Bally, who kindly made them availble prior to their entering the public domain.

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Because of the need to compare data from a variety of sources and pointings, we cast all of the observations into a format with an orientation of north up and carefully determined the necessary shifts for producing coaligned images. The northern field is highly irregular in outline since it combines two sets of data (ours and Bally's). Jumps in the background are seen at some of the junctures of data sets (both HST and infrared) due to inaccuracies of the flat field corrections. We have allowed these to remain since they are cosmetic rather than substantial and actually help to delineate the boundaries between the data sets. Position references were always obtained using the stars from the list of Jones & Walker (1988) after applying a $+0.059^{s}$ correction in Right Ascension to all their values (O'Dell & Wong 1996 and references therein).

We concluded our data reduction by preparing color coded images of each field. In our detailed analysis we used various color combinations and examined the high quality monochromatic images in considerable detail. The [O I] and [S II] images were very similar in the HH objects and could often be used in combination to improve the signal to noise ratio. In addition, much of the background nebula's contribution could be removed from them by subtracting the combined Hα and [N II] images, rendering the [O I] and [S II] much more visible.

3. HH Systems in Orion and the Engines that Power Them

HH objects typically consist of a series of bow shocks that mark the location of radiative shocks along a jet. Stellar jets emanate from young stars surrounded by accretion disks, so it is usually possible to identify the star responsible for the outflow in those cases where HH objects are aligned. A cursory examination of the images reveals at least two different systems of HH objects in the Orion nebula region. We show below that the first system is itself composed of at least two distinct subsystems.

3.1. The North HH Object System

We will call the first system the North System and discuss it in this section. As we'll see, it actual breaks down into an Inner and Outer pair of systems. The possibility of its existence was first articulated in the proper motion study of Jones & Walker (1985) who pointed out that HH 201, 205, 206, and 210 seemed to be moving rapidly away from a common center near the location of IRc2, thus extending the argument of Axon & Taylor (1984) that there could be such a system associated with the compact infrared sources embedded in OMC-1. These arguments were strengthened by the publication of the infrared images of A&B which not only showed intense H_2 regions clustered about IRc2 and BN, but also faint H_2 fingers which extended to projected distances of 0.08 pc from there. The most recent study of H_2 (McCaughrean & Mac Low 1996) isolates the H_2 emission better by accurate subtraction of the nebular and scattered continuum. The new H_2 images reveal an additional finger in approximately the 8 o'clock position from the center, but the images do not cover the richest region of fingers to the north. In our discussion of these fingers we will refer to them by clock based analogies.

The North System is illustrated well in Figure 1. In this image we have shown A&B's H_2 image being shown in red, [S II] plus [O I] emission in green and Hα emission in blue. The strong difference in surface brightness in H_2 between the fingers and the central region was suppressed by dividing the H_2 image by a low order fit to itself. We see that there are seven H_2 fingers. HH 210 falls at the tip of the 11 o'clock finger and HH 206 and HH 207 fall along the edge of the 1 o'clock finger at whose tip lies HH 205. We have outlined the fingers as they appear on the best video screen displays and have marked in the proper motions of the HH objects determined in the studies of Jones & Walker (1985) and Hu (1996b), projected at the present rate back for 400 yrs.

A detailed examination of the images show that fingers 10:30 through 1:30 all have

[O I] and [S II] emission at or near their tips on the new HST images. The high extinction expected in the PDR beyond the main ionization front of the Orion Nebula (Tielens & Hollenbach 1985) together with the appearance of both the H_2 and the easily obscured optical emission indicates that the tips of these fingers must lie close to the ionization front which forms the near boundary of OMC-1. This conclusion is strengthened by the fact that there is an excellent correlation of appearance of the combined low ionization optical [O I]+[S II] lines (Figure 2) and the infrared [Fe II] lines, which should arise from very similar regions. This means that the northernmost fingers form a rather homogenous set of objects, probably having common conditions. The fact that the radial velocities of HH 205, 206, 207, and 210 are highly blueshifted (180, 200, 200, 425 km s^{-1} Axon & Taylor 1984, Taylor *et al.* 1986, Allen & Burton 1994, Hu 1996b); all radial velocities in this paper will be heliocentric unless otherwise noted) is consistent with the fingers being a near surface phenomenon driven by an inner source.

Examination of the material going into Figure 1 indicates that the fingers falling between 10:30 and 1:30 determine only an imprecise common center, but one that is about at the star 138-207 (using the Orion position dependent designation system of O'Dell & Wen (1994)) which is Jones & Walker (1988) 423 Fig. 2). This center lies about midway between HH 208 and 209, rather than at IRc2, the usual source that is identified. This is not to argue that 138-207 is indeed the source, rather, that it falls closer to the ill defined common center than does IRc2+BN. However, the uncertainty in this center due to the errors in the proper motions (about 15°) is large enough that we cannot exclude the possibility that the fingers originate from IRc2+BN.

Figure 2 shows the central region of Figure 1 and can be used for discussing whether or not the inner northern HH objects (201, 208, 209) are related to the system defined by the northernmost fingers discussed above. The inner northern HH objects share the common property of being quite blueshifted, with radial velocities of 310, 225, and 250 km s^{-1} respectively (Axon & Taylor 1984, Burton & Allen 1994, Hu 1996b) and HH 201 has a similar high proper motion (Jones & Walker 1985, Hu 1996b). HH 201 resembles HH 205 and 210, while HH 208 and 209 are very different in form, not at all resembling a shock seen edge on but could be shocks viewed almost along the line of the driving jet.

Examination of the symmetry of these inner northern HH objects indicates no common origin for them. HH 201 seems to be the superposition of two quite symmetric and parallel sources or clumps in a single bow shock. The symmetry axis runs close to both the IRc2 and BN infrared sources and to HH 208, although the uncertainties preclude a detailed fix on a driving source. If the same source that drives the outer northern HH objects also drives HH 201, the source must lie somewhere south of star 138-207. As seen in Figure 3, HH 209 has a clumpy structure that lacks any obvious symmetry. A region of [O I] and [S II] emission exists just to the north of HH 209, and there is also H_2 emission immediately north of IRc9. Together, the optical and H_2 emission lie along a line towards the BN+IRc2 region and the apparent common center of the Northern HH objects and HH 201.

Figure 2 shows that HH 208 is accompanied by a collection of clumpy material to its northwest, which, like HH 208, is highly blueshifted in recent Fabry-Perot images taken by Hartigan, Morse, & O'Dell (in preparation, hereafter HMO). We may see evidence of a jet that drives HH 208 and its further associated region in our images. Although difficult to see in Fig. 2, there is a faint, broad ($1''$) linear feature exactly along the line passing through HH 208 and its companion shock at a position angle of 305°. This linear feature passes about $1''$north of 147-234 and fades away near the star 154-240, which is certainly a young low mass star since it is a well defined proplyd (O'Dell & Wong 1996). This association is the strongest evidence for a source of a driving jet in M42 and will be considered in HMO.

Figure 2 shows well a feature marked as 127-147 which is the optically brightest part of a low ionization finger extending out towards the WNW. The HMO spectra indicate a radial velocity of about -200 km s^{-1}, so that it too is probably is an HH related object. There is an additional feature that extends ESE from just above 138-207 which was first pointed out by Hester *et al.* (1991). Figure 2 shows that a faint linear feature extends beyond that star and points directly at 130-201. Such an alignment may only be fortuitous, as there is no evidence of high radial velocities in the brighter east part of this feature (O'Dell *et al.* 1991).

In summary, we can say that the North HH objects fall into a similar class according to their velocities. Unlike HH 201, HH 210, and HH 205, which show clear bow shock shapes, the shocked gas in and around HH 208 and 209 is more clumpy and irregular. All of the North HH objects are consistent with a common center just south of 138-207, with the exception of HH 208, which may originate from the pre-main sequence star 154-240.

3.2. The Southern HH Object System

The division of the M42 HH objects into Northern and Southern Groups is based on their apparent centers. All of the objects included in the northern system are either near or have a symmetry center in the BN+IRc2 region. Those we group as the Southern HH Objects don't have such a simple delineation, but clearly stand in contrast with the Northern HH Objects. The brightest members of the Southern Group are HH 202, 203, and 204, and we will also present arguments in this section for there being several additional members. All of these objects differ from the Northern Group objects, in that they lack H_2 emission and are about an order of magnitude larger in size.

The brightest members of the Southern Group can be seen well in the color HST mosaic image of M42 presented by O'Dell & Wong (1996). HH 202 is located to the WNW from θ^1C Ori and HH 203-4 are in the SW part of M42 very near the hot star θ^2A Ori. The proximity of HH 203-4 to such a bright star led Taylor & Munch (1978) to argue that the HH objects represent a stellar wind interaction, a position now superceded by the view that these objects represent jet driven shocked material. The Orion mosaic image shows well how HH 202 and HH 203-4 seem to fall on opposite ends of the same line of symmetry, with a separation of $210''$, although this property has been obvious and appreciated for some time from good ground observations.

HH 202 was discovered by Canto *et al.* (1980), who showed that at the end of a long concave form there were two bright knots, as illustrated best in the [S II] image of Figure 4. The north knot was studied at high spectral resolution in [S II] by Canto *et al.* and they determined that the radial velocity peaked at about -42 km s^{-1}, indicating a blueshifted flow of about 68 km s^{-1} with respect to OMC-1. Similar results were obtained by O'Dell *et al.* (1991) who studied the south knot in [O I], [S II], [N II], [O II], [S III], and Hα. The latter study was able to determine that there seems to be a large scale shock structure that is moving at about -20 km s^{-1}. Superimposed on this is the south knot, which is moving at about -30 km s^{-1}. Figure 4 shows that the north knot is quite low ionization, while the south knot possesses strong [O III] emission. There is extended [O III] emission throughout the long concave form.

The proximity and near alignment of HH 203 and 204 argues that they are related or at least share a common source, but there are important differences. The more northerly of the pair, HH 203 resembles a truncated bow shock. Such a form can be explained as due to a jet impinging on a cloud with a density gradient (Henney 1995). Although the agreement with such a model is quite good (Hu 1996b), it may also be possible to explain the asymmetry in HH 203 from differences in the pre-shock ionization. HH 204 is a highly filamentary bright knot at the end of a rather symmetric cone that resembles a bow shock, even though the high excitation line of [O III] does not occur at the apex of the bow like it usually does in other HH objects. As we discuss in the next section, the excitation in this object appears to be controlled by a mixture of local shocks and external ionization from θ^1C Ori. The velocity of HH 203 is about -50 km s^{-1} and -25 km s^{-1} (Taylor & Munch 1978, Walsh 1982, O'Dell *et al.* 1993b). The proper motion of Cudworth & Stone (1977) indicate a tangential velocity of HH 204 of 70 km s^{-1}.

Both the HH 202 and HH 203-4 regions share the common property of having extended [O III] emission within an envelope that has low ionization peaks at the apices of the bows. There is no indication of such a property in any of the northernmost HH objects (which we believe arise from within OMC-1). While the North HH objects may have a higher density and hence have a shorter cooling length, a more significant difference in the environments of the North and South systems is the preshock ionization, which is maintained at a high level in the southern system by ultraviolet radiation from θ^1C Ori.

The other cataloged M42 HH object is HH 269, which differs in many ways from the others. It is an east-west oriented elliptical ring marked by two bright knots on the ends of the long axis. A recent study of HH 269 by Walter *et al.* (1995), where monochromatic HST images are published, indicates that the object is quite low ionization and the east knot has V = -13 km s^{-1} and the west V = -23 km s^{-1}. HH 269 has strong low ionization lines, but also appears in the [O III] images, probably because it too is illuminated by θ^1C Ori.

We know that M42 is primarily a high density blister type H II region on the near side surface of OMC-1. The Trapezium Cluster of stars, which includes the dominant source of photoionization θ^1C Ori, is located nearer to us than the main ionization front within a region of low density and high ionization. Overlying all of this is a highly irregular neutral lid of dust and gas. The low ionization and blue shifts of HH 202, 203+4, and 269 indicated that they all form in the foreground neutral lid, a conclusion supported by the presence of extended [O III] emission in each.

There are numerous additional features that are best associated with the Southern System. Examination of the HST mosaic image of M42 shows that there is a more homogeneous ring of similar form and size immediately to the east of HH 269 and that object in turn is adjoined by a similar size ellipse whose northern edge appears in both extinction and emission. A line drawn along these three objects intersects the line between HH 202 and HH 203-4 at a region rich in blue shifted high ionization shocks (O'Dell *et al.* 1993b). These latter shocks emanate radially from a point near the center of the intersection of the two lines. This intersection region contains many pre-main sequence low mass stars and is one of the subjects treated in HMO. The high ionization shocks, which are visible only in [O III] and Hα, are probably formed in the low density photoionized gas that lies in the low gas density region between the main ionization front and the foreground neutral lid.

4. The Shock Excitation Paradigm

The brightest portions of stellar jets typically appear as a series of bow shocks that form as the young star ejects material in sudden bursts (*e.g.* Reipurth & Heathcote 1993). The line excitation at the apex of a bow shock is always higher than in the wings because the effective shock velocity is higher at the apex. For example, [O III] emission only exists near the apices of bow shocks in HH 34S (Morse *et al.* 1992), HH 111L (Morse *et al.* 1993b), and HH 1 (Solf *et al.* 1988), whereas Hα and [S II] also emit along the wings of the bow. Often the shock velocities inferred from the emission line ratios in stellar bow shocks are several hundred km s^{-1} lower than the space motions measured from proper motions and radial velocities, but such differences can arise if the bow shock moves into the wakes of previous ejections. Sometimes a reverse shock or 'Mach disk' is visible as fast material in the jet overtakes material behind the bow shock (*e.g.* Heathcote *et al.* 1996).

It is a challenge to apply bow shock models to HH objects in the Orion Nebula because there are many possible exciting sources and much of the ambient gas is heated by photoionization. Nevertheless, it is instructive to begin with this paradigm as a starting point for any object, and we will do so in what follows.

HH 203 and HH 204 resemble bow shocks in morphology, but as Figure 5 shows, the [O III] emission from this region does not come from the apex of the bows, but instead occurs primarily in a diffuse region along the southwestern portion of the objects. We would expect the apices of HH 203 and HH 204 to lack [O III] if the shock velocities were $\lesssim$ 90 km s^{-1}. Both HH 203 and HH 204 are known to be blueshifted and the velocities are relatively low. The [O I] in the frothy head of HH 204 is considerably more clumpy than [S II], perhaps because [O I] has a higher critical density than [S II], an interpretation consistent with the results of Walsh (1982) who found densities well over 10^4cm^{-3}. The Hα, [O I], [N II], and [S II] emission concentrate in clumpy structures that define an asymmetrical bow-shaped structure (HH 203) followed by a more symmetrical bow (HH 204). The lack of symmetry in HH 203 probably arises from an increasing preshock density towards the northeast in this object. These 'comma-shaped' structures have been observed in other objects (*e.g.* Hartigan *et al.* 1986) and are present in numerical simulations of bow shocks that propagate through a medium with a lateral density gradient. We attribute the distribution of [O III] to differences in the way that θ^1C Ori illuminates this region of the nebula. Hence, in these objects the line excitation tells us little about the shocks.

As in the case of HH 203/204, the [O III] emission in HH 202 (Figure 4) does not originate primarily at the apex, but instead radiates over the entire cavity. The lower excitation lines radiate most strongly in a bright region near the apex of HH 202 and in a region along the north shoulder of the cavity. An additional hemispherical bubble appears in [O III] and Hα to the northwest of HH 202 (the direction away from the

Trapezium). Overall, the proximity of θ^1C Ori appears to cause the line excitation HH 202 to be dominated by photoionization, though the observed radial velocities imply that some shocked gas is mixed in the region (Canto *et al.* 1980).

Another HH object in the Orion Nebula that resembles a bow shock in both morphology and line excitation is HH 201. This object has a bright [O III] peak at its apex (Figure 3), with more extensive Hα following along the wings and the [S II] outlining the entire bowshock. As in HH 210, the bow shock seems to be breaking into multiple pieces as it progresses through the nebula. Given the large radial velocity of this object (-310 km s^{-1}), it is surprising that [O III] does not emit over a larger fraction of the bow shock, since [O III] should become observable when the component of the velocity perpendicular to the shock exceeds 90 km s^{-1} . It is possible to explain this behavior if the preshock medium moves outward at a substantial fraction of the bullet velocity. This explanation is required to explain the extent of [O III] in other HH objects as well (see below).

HH 210 is a remarkable object whose [S II] image appears as a delicate extended finger of emission that points away from θ^1C Ori. Though this object has no significant H_2 emission, it resembles the HH knots seen at the heads of the other H_2 fingers in morphology. The line excitation in HH 210 shows good qualitative agreement with a bow shock model. Here Hα and [O III] emit in two bright areas near the apex, with the Hα extending somewhat further into the wings than the [O III]. This gradient in line excitation from apex to wing is expected from a bow shock. The two peaks may arise if the bow is breaking up into smaller pieces owing to Rayleigh-Taylor instabilites, as has been proposed for some HH systems (*e.g.* HH 2). Alternatively, since the forward peak is relatively weaker in [O III], it may represent a precursor moving ahead of the main bow-shock. The relative lack of Hα emission from the [S II] emitting wake is unexpected, as Hα typically outlines the location of shock fronts in stellar jets. However, the wake disappears into a bright Hα background caused by the Orion nebula in the southern portion of HH 210, and this background makes it difficult to observe the shock structures there in Hα. The southern portion of HH 210 dips into the [O III] region excited by θ^1C Ori.

Like HH 210, HH 205 lies far enough from θ^1C Ori so that its line excitation is not dominated by photoionization. HH 205 clearly defines a bow shock, both in morphology and in line excitation. The [O III] is confined to a small arcuate region near the head of the bow, with Hα extending more into the wings and [S II] emitting over the entire bow shock. These morphologies are in agreement with a bow shock model. Proper motion of the system is in the direction of the head of the bow, as is also true for HH 210. Both HH 205 and HH 210 have high enough space velocities to account for [O III] emission at their apices.

The wings of the bow shocks in HH 201 and HH 210, and to a lesser degree HH 205, all exhibit a triangular shape in the [S II] images of Figs. 3 and 6. The bow wings of HH 201 and HH 210 define opening angles of 29° and 25°, respectively. We can calculate the Mach number from these angles if we know the inclination to the objects. High resolution spectra of the [O I] line profile by Hu (1996) suggest orientation angles of between 0 and 15° ($\phi =$ 90° if the bow shock moves in the plane of the sky). However, if HH 201 and HH 210 were really coming almost directly toward the observer, it is difficult to understand why these objects have such pronounced conical shapes. If we adopt the full velocity width of the [O I] profiles from Hu (1996) as a measure of the true velocity of these objects (cf. Hartigan *et al.* 1987) then the observed proper motions imply $\phi \sim 33°$ for both HH 201 and HH 210. The intrinsic opening angles for HH 201 and HH 210 are then $\sim 14°$, which corresponds to a Mach number of 8. For a sound speed of 16.6 km s^{-1}(at T=10^4 K), this implies a bow shock velocity of 133 km s^{-1}. This is consistent with the observation of [O III] emission only at the bow shock tip, but it is not consistent with the line widths of order 300 km s^{-1}(Hu 1996). The large line widths can be reconciled with the bow shock opening angles if the

Mach angle corresponds to an Alfven speed of about 35 km s^{-1}. This in turn requires a magnetic field of several hundred microGauss in the compressed post-shock flow Raymond *et al.* 1988).

To the south of HH 205 along the same H_2 finger are HH 206 and HH 207, and to the east of these is a complex of knots we call HH 207 E (Figure 6). HH 206 resembles its northern neighbor both in its bow shock morphology and in its line excitation. As in HH 210 and HH 205, HH 206 has [O III] emission at the apex, followed in the wings by Hα and [S II]. HH 207 appears to be a low-excitation analog of HH 206, with the bow well-defined in [S II], Hα more confined towards the apex, but no [O III]. While this scenario is consistent with a low velocity ($\lesssim 90 \mathrm{kms}^{-1}$) bow shock, such a low excitation is puzzling in light of the high radial velocity and proper motion of this object. The easiest way to explain a high velocity low-excitation HH object is if the object moves into the wake of a previous ejection, so that the effective shock velocity is the difference between the velocity of the knot and that of its preshock gas. Such a scenario makes sense for HH 207, which follows in the wake of HH 206 and HH 205. An extremely strong magnetic field can also lower the line excitation in a shock (Hartigan, Morse & Raymond 1993). The complex of low-excitation [S II] knots in HH 207E does not outline a well-defined bow shock morphology and nothing is known about the proper motions and radial velocities of these objects. Hence, it is premature to draw any conclusions about these objects here.

HH 208 and HH 209 both appear only in the [S II] and [O I] images and show a deficit of [O III] surface brightness in the nebular background. The strength of the low ionization lines relative to Hα indicate that they are formed in low velocity shocks, but like HH 207 this is incompatible with their known high radial velocities. The deficit in [O III] is similar to that seen in the Orion proplyds (O'Dell & Wen 1994) and indicates that the dust concentration in the shock is strong enough to block out the background nebular emission. The bright knot of HH 208 is surrounded by a fainter, almost spherical shell which is elongated to the SE. HH 209 shows three bright knots imbedded in a circular disk of emission and does not resemble any expected shock structures. The faint star 2″ to the north of HH 208 has a weak extension in Hα along a direction away from HH 208. Whether or not this feature might represent a jet from the star whose opposite lobe produces HH 208 can be tested with proper motion observations of HH 208 or with radial velocity measurements of the Hα feature.

5. Discussion

There appear to be at least two types of HH objects in the Orion Nebula region. HH 205-6-7, 210, and 201 have high spatial velocities, quasi-symmetric forms and small sizes. These are probably shocks in the dense PDR region, where the cooling lengths would be correspondingly short and the objects smaller. These objects all have a common region of origin, although it is unlikely to be a single point of origin. It is interesting that if one accepts large errors in the proper motion directions and fits HH 201, 205, 206, and 210 to a common center, there appears to be a common epoch of origin, which is about 900 years ago (Hu 1996b). The second type of HH object includes HH 202 and HH 203-4, which are much larger, have lower spatial velocities, and have extended [O III] emission. These are probably shocks formed in the neutral lid overlying the Orion Nebula and have their high ionization sustained by flux from θ^1C Ori which enters the lid behind the shock. The extinction of the background nebular emission in [O III] by HH 208 and HH 209 would require them to be ahead of the main ionization front, and therefore would be associated with the lid, so that they represent characteristics of both the North and South systems.

HH 208 may be associated with a jet from 154-240 or from the star just to its north, while HH 209 lacks any symmetry, apparant jets, or proper motions, hence is impossible to identify with a candidate source. HH 269 is possibly the archtype of a third class of HH object in Orion, being a knotted oval in form, in line with at least one similar object, and possessing extended [O III] emission, again arguing that it arises in the lid.

5.1. The H_2 Finger System

The mechanism driving the fingers that are seen best in H_2 have been discussed by the discoverers (Allen & Burton 1993), Stone *et al.* (1995), Schild *et al.* (1996), and McCaughrean & Mac Low (1996). None of these papers seem to consider the elongated clumped flow recently seen in the same area in NH_3 (Wiseman & Ho 1996) which provides evidence that massive clumps of material exist within OMC-1. These clumps raise the possibility that the fingers exist simply because they are the regions where wind driven material finds it easiest to penetrate, an idea recently pursued by Gvaramadze (1997). The operation of such a mechanism may be supported by the fact that the PhD thesis of Tedds (1996) argues that the extinction along the fingers is relatively constant but is higher between them.

The inner part of IRc2 region shows enormous detail in the H_2 images, suggesting that all structures, including the fingers, have their origin in this inner region rather than by shaping of a more general stellar wind. Recent infrared Fabry-Perot images at 14 km s^{-1} FWHM resolution (Chrysostomou *et al.* 1997) detect a 5 km s^{-1} difference in velocities along a NW-SE line, which indicates a tilted bipolar flow. They even see profiles showing line splitting in localised regions in the central 30" around BN, with features moving at both red- and blue-shifted velocities with respect to OMC–1. They argue that these represent bow-shocks seen in just the H_2 lines, and are produced by the same mechanism giving rise to the fingers, the latter being where the ambient cloud density is less.

The fact that essentially all of the infrared fingers that fall within the region searched with HST in [O I] and [S II] have optical counterparts argues that they all penetrate to at least near the observer's side of OMC-1, which would not be the case for any of the mechanisms having them shaped in the central region. The instability mechanism proposed by Stone *et al.* (1995) can also occur if a stellar wind driven shock reaches a zone of rapid density decrease. Since this would selectively produce objects near the surface, such a mechanism becomes attractive, but requires that the density gradient be encountered deep within OMC-1.

The good correlation of the [O I] and [S II] visual images with the infrared [Fe II] images indicates the tips uniformly suffer little extra extinction. This is contradicted by the results of Chrysostomou *et al.* 1997 who argue that the visual extinctions of HH 201, 203, 207,and 210 range from 4.5−8.7 magnitudes, as determined by two infrared [Fe II] lines arising from the same upper level. These extinction values are about five times the average for M42 and don't show up in the point by point mapping of M42 extinction (O'Dell *et al.* 1992). Certainly HH 201, 207, and 210 must be shielded from photoionization by θ^1C Ori but it takes relatively little corresponding visual extinction to produce this. In the case of HH 203, where the [Fe II] extinction is like the others, the extinction could only be produced in the compression immediately in front of the shock and there is little reason for expecting it to be similar to the values for the other three, which are formed in OMC-1. Reconciliation of these results could arise from small differences in the calibration of the infrared system and/or the projection from a small frequency difference into the visual.

If one accepts that the HH objects of the North System are on the surface of OMC-1 then the fact that they are traceable back towards the center means that whatever is producing the H_2 fingers is also preferentially working on the observer's side of OMC-1. This could be explained by arguing that the most obvious energy source, IRc2, is located in a region relatively near the surface, so that there is a strong preferential density gradient, which allows flow of wind driven material towards the observer. The most likely mechanism for shaping this flow is large scale mass concentrations. Such a scenario seems much more likely than the existence of a host of bullets passing through OMC-1, reaching the surface at the same time, and all having suffered little or similar amounts of deceleration.

As an aside we point out that if the driving mechanism involves a global transfer of momentum, rather than a local source such as a jet, then the fingers and tips in the North System should not be classified as HH objects. The commonality of appearance would indicate the shared importance of shock excitation, but would not associate the North System objects with lower mass pre-main sequence stars with jets, which seems to be the common factor in true HH objects. Uncollimated ejection would still arise from accretion by a pre-main sequence star, which would give the fingers a driving source similar to the jets producing the "classical" HH objects.

The highest excitation optical lines occur at the tips of the H_2 fingers, as expected in a bow shock model. However, in addition, any model of the fingers will have to reconcile the high radial velocities and large proper motions with the relatively low excitation line emission observed. In a standard bow shock model, the low excitation and high velocities can be explained if either the gas ahead of the fingers moves outward at several hundred $\mathrm{km\,s^{-1}}$ with respect to IRc2 or if the magnetic fields there are enormous (milligauss strengths). It will be important to predict how the shock velocity should vary along arcs formed by a fragmenting stellar wind, so that this prediction can be compared with observations. If previous jets and winds have indeed punched several holes through OMC-1 and we are observing the result of a stellar wind shell as it funnels along these tubes, it makes sense that the shock velocity should be highest at the apex, where the velocity jump should be the largest. This model also predicts that the space velocities of the fingers will be much higher than their shock velocities, as is observed to be the case.

5.2. Possible Jet Related Features

If the other objects discussed are true HH objects, why (with the possible exception of HH 208) do we not see the driving jet? Part of the problem throughout the nebula is that the bright background photoionization sometimes makes it difficult to observe any faint line emission from weak shocks in a flow. In the case of the South System HH objects the lack of a visible jet may lie in the fact that the jets are passing through a medium that has been highly photoionized, so that the usual low ionization tracers are not available. This conclusion is strengthened by the observations of Hu (1996a) that show an apparent high velocity [O III] jet leading into HH 203, a conclusion confirmed and extended in HMO.

In the case of the southern object HH 269, we can envision a scenario that would describe both its form and also its similar companion feature to the east. The 21 cm absorption study of HI in the lid (van der Werf & Goss 1989) not only established the presence of the lid, but also showed that it was highly irregular and was grouped into three velocity systems. The form of HH 269 and the similar object to its east could be due to a single jet having passed completely through two clouds within the lid, leaving behind two rings of shocked material.

Finally, we must address the problem of why all of the HH objects in this region show only blue shifted lines with respect to OMC-1. We have explained this as one set of objects arising in the portion of the PDR of OMC-1 that faces the observer and the other set arising from the foreground lid. The second set of objects presumably have sources that exist in the open cavity near the Trapezium stars, which means that their bipolar jets would have corresponding antipodal features. Since these jets would be impacting the main ionization front behind the Trapezium, which is both of much higher density and ionization than the regions giving rise to the blue shifted HH objects, it is likely that they will very different ionizations, much smaller sizes, and possibly lower relative velocities than the observed objects. A search for such objects is being pursued in HMO.

5.3. Concluding Remarks and Acknowledgements

Since objects HH 201 and HH 203+204 both appear in the higher resolution CCD of WFPC2, it is hoped that very accurate proper motions of these objects can be obtained with a second set of similar observations. This expectation is based on the fact that the study of Jones & Walker (1985) and Hu (1996b) indicate that HH 201 is moving about $0.08''$/yr and Cudworth & Stone (1977) determine that HH 204 is moving about $0.03''$/yr. The highest resolution WFPC2 pixels are $0.046''$, so that good proper motions should be feasible in only a few years.

Although we have used the standard catalog listing for the known HH objects in this paper, e.g. HH 201, this study shows that there are so many shocked features that it is probably wise to begin use of an Orion specific coordinate based system of designation for the secondary and new systems. The details of such a system are described in O'Dell & Wen (1994). Digital copies of the monochromatic images shifted into the composite, north oriented format are available through the senior author by ftp transfer (spacsun.rice.edu;directory pub/cro/Cycle5HH).[Note to referee and coauthors. this capability will be set up after our paper has been accepted for publication.]

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Fig. 1.— This color coded image was formed by the use of A&B's H_2 as red, the HST [S II]+ [O I] images as green, and Hα as blue. The red "halo" around the stars is due to the lower angular resolution of the groundbased images of A&B. We have labeled the location of the previously known HH objects, the BN source, and the numbered IRc radio and infrared sources. The long straight arrows indicate the proper motion of the measured HH objects over the last 400 years. The curved lines outline HH 202, a few new HH objects, and the border of the infrared fingers determined by a detailed examination on a good video screen. North is at the top and East is to the left.

Fig. 2.— The central region imaged as the north field by HST is shown as a combination of the [S II] and [O I] images. The left image is without labeling and the right uses labels similar to Fig.1. The arrow indicates the proper motion of HH 201 over the last 200 years. The middle thin straight line is along a long linear feature that points towards star 130-201, although this feature is probably a portion of the ionization front viewed edge on. The lower straight line is drawn through HH 208 and the symmetric grouping of shocks NW of it. It falls along a long linear feature extending past 147-234 and directly towards the proplyd 154-240. This may be the jet that is driving HH 208.

Fig. 3.— Negative monochromatic HST images are shown in [S II], Hα, and [O III] for HH 201, 205, 207, 208, and 209. The scales and orientation are indicated.

Fig. 4.— The same as Fig.3 except depicting only HH 202 and at a more compressed scale.

Fig. 5.— The same as Fig.3 except depicting both HH 203 (top middle) and 204 (bottom left) and at a more compressed scale.

Fig. 6.— The same as Fig.3 except depicting HH 206, 207e, and 210 at a more compressed scale.