HST NICMOS Images of the HH 7/11 Outflow in NGC1333

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ABSTRACT

We present near infrared images in H\textsubscript{2} at 2.12\textmu m of the HH 7/11 outflow and its driving source SVS 13 taken with Hubble Space Telescope NICMOS 2 camera, as well as archival H\alpha and [S II] optical images obtained with the WFPC2 camera. The NICMOS high angular resolution observations confirm the nature of a small scale jet arising from SVS 13, and resolve a structure in the HH 7 working surface that could correspond to Mach disk H\textsubscript{2} emission. The H\textsubscript{2} jet has a length of 430 AU (at a distance of 350 pc), an aspect ratio of 2.2 and morphologically resembles the well known DG Tau optical micro-jet. The kinematical age of the jet (\sim 10 yr) coincides with the time since the last outburst from SVS 13. If we interpret the observed H\textsubscript{2} flux density with molecular shock models of 20-30 km s\textsuperscript{-1}, then the jet has a density as high as 10\textsuperscript{5} cm\textsuperscript{-3}. The presence of this small jet warns that contamination by H\textsubscript{2} emission from an outflow in studies searching for H\textsubscript{2} in circumstellar disks is possible. At the working surface, the smooth H\textsubscript{2} morphology of the HH 7 bowshock indicates that the magnetic field is strong, playing a major role in stabilizing this structure. The H\textsubscript{2} flux density of the Mach disk, when compared with that of the bowshock, suggests that its emission is produced by molecular shocks of less than 20 km s\textsuperscript{-1}. The WFPC2 optical images display several of the global features already inferred from groundbased observations, like the filamentary structure in HH 8 and HH 10, which suggests a strong interaction of the outflow with its cavity. The H\textsubscript{2} jet is not detected in [S II] or H\alpha, however, there is a small clump at \sim 5'' NE of SVS 13 that could be depicting the presence either of a different outburst event or the north edge of the outflow cavity.

Subject headings: ISM: Herbig-Haro objects — ISM: individual (HH 7/11) — ISM: jets and outflows — stars: formation — stars: mass loss

1. Introduction

Herbig-Haro (HH) objects trace optically the mass loss process from young stellar objects (YSOs) and their interaction with the surrounding medium (Reipurth & Bally 2001). Because of their mor-
phology, energetics and size, HH objects are an integral part of the star formation process and its effect on molecular clouds. HH 7/11 is a chain of HH objects in Herbig’s photographic plate catalogue (Herbig 1974), located in the very active star forming region NGC 1333 (Aspin et al. 1994; Bally, Devine & Reipurth 1996) at a distance of 350pc (Herbig & Jones 1983). From the ground, at optical wavelengths, the HH 7/11 system is defined by an arch-shaped morphology (blue lobe) that spans ∼ 2′. The red-shifted counter-lobe is detected in the near infrared (NIR), e. g. at 2.12μm in the H$_2$ (1,0) S(1) line, and displays a more chaotic structure (Stapelfeldt et al. 1991; Garden, Russell & Burton 1990). Recent interferometric observations (Bachiller et al. 2000) have convincingly demonstrated that SVS 13 (Strom, Vrba & Strom 1976) is the driving source of the HH 7/11 outflow. SVS 13 has a Class 0/I spectral energy distribution (Bachiller et al. 1998) and a luminosity of ∼ 85 L$\odot$ (Molinari, Liseau & Lorenzetti 1993).

Detailed optical spectroscopic observations of HH 7/11 show a complex velocity field and a low excitation nature, consistent with shock velocities of 30-60 km s$^{-1}$ (Solf & Böh 1987; Böh & Solf 1990). NIR spectroscopy displays a rich H$_2$ vibrational spectra and strong [Fe II] 1.257 and 1.644μm lines (Gredel 1996; Everett 1997), again consistent with collisional excitation by shocks. Far infrared spectroscopy, which includes the emission of molecular species (like H$_2$, H$_2$O and CO) and atomic fine structure lines (like [O I] 63μm and [Si II] 34.8μm), requires both J-type and C-type shocks of 15-30 km s$^{-1}$ to explain their ratios (Molinari et al. 2000).

In this paper we present new high angular resolution (FWHM=0.1′′) Hubble Space Telescope (HST) NICMOS H$_2$ images at 2.121μm of HH 7/11 and its source SVS 13, as well as archive optical images in Hα and [S II] taken with the WFPC2 camera at a similar epoch.

2. Observations and Data Reduction

The NICMOS observations were made with Camera 2 which has a nominal plate scale of 0.′′0755± 0.′′005 per pixel. The observations were carried out on January 9, 1998. Three filters were selected for observation, F187N (Pa), F204M, and F212N (H$_2$). Two dithered images were taken with the three filters sequentially at each of five pointing positions. Integration times per frame were 40 sec at F187N and F204M, and 80 sec for F212N, resulting in a total integration time of 80 sec in F187N and F204M, and 160 sec in F212N. Dark frames used for subtraction were taken at the end of the observations.

The images were reduced using the IRAF data reduction package NICRED, written for HST/NICMOS data by McLeod and Rieke 1997). Darks were created using the observed dark frames with the routine NICSKYDARK, part of the NICRED package. The flats were those produced by M. Rieke to be used with NICMOS data. After dark subtraction and flat fielding, the images were cleaned for any additional bad pixels using the IRAF routine IMEDIT.

The NICMOS pixels are non-square by ∼1%, and prior to shifting and adding, the pixels were
rectified using IDL procedures developed for the Image Display Paradigm #3 (IDP3) \(^4\) software package (Stobie et al. 1999). IDP3 was then used to shift the data, aligning them using the world coordinate system values, and median combine all the images. The combined images were then flux calibrated using the values derived by M. Rieke for NICMOS data (1999 private communication).

Observations on the adjacent narrow band continuum filters to the F212N and F187N were not taken due to time constraints, so a method had to be developed to provide an useful empirical estimate of the continuum in the narrow band filters using the F204M continuum image. The continuum subtraction was performed interactively using IDP3. Since the continuum image is taken with a much wider filter, and at a central wavelength not immediately adjacent to the narrow band filter, they needed to be scaled prior to subtraction. In IDP3, the continuum image was precisely aligned with the emission line image using the SVS 13 star, and subtracted from the narrow band image with a slowly increasing scale factor until the variance in the differenced image of SVS 13 was minimized.

The WPFC2 observations were taken from the HST archive and reduced using the standard IRAF STSDAS packages. The optical images unfortunately do not cover the entire HH 7/11 outflow; the brightest HH 7 object is partially missing at edge of one of the detectors. The lack of reference stars between the frames, implies that the detailed comparison relies on the accuracy of the coordinates systems adopted by NICMOS and WFPC2. The source SVS 13 was used to align the images, first by centroiding, then by minimizing the residuals of differenced images. A summary of the observations is in Table 1.

3. Results and Discussion

Before comparing the high resolution images from HST, let’s briefly revise what is observed from the ground to emphasize the differences and similarities between the emission of the atomic gas and the warm molecular Hydrogen, in particular because the WFPC2 images do not cover the entire object. In Figure 1, we compare two images of HH 7/11 placed on the same scale, one taken in \([\text{S II}] \, 6717/31\, \text{Å}\) (from Noriega-Crespo & Garnavich 2001), and other taken in \(\text{H}_2\) at \(2.12\, \mu\text{m}\). The \(\text{H}_2\) image was obtained with the Fred L. Whipple (FLWO) 1.2 m telescope and the ADS SBRC Camera in 1997 on October 10, with an angular resolution of \(\sim 1.2''\) (P. Garnavich, Private Communication). There are \(\text{H}_2\) images at \(2.12\, \mu\text{m}\) of HH 7/11 obtained with higher angular resolution, \(\sim 0.5'' - 0.6''\) (see Chrysostomou et al. 2000 for details) which show an even more clear view of the outflow. From Figure 1 we notice, (i) the different structure of HH 7, the leading Working Surface (WS) of the jet, which at optical wavelengths shows two well separated regions that have been identified with the bowshock and the Mach disk; (ii) the absence of a compact counterpart in \(\text{H}_2\) to the optical HH 11 knot; and (iii) that despite these differences there is a ‘one to one’ correlation between the main “knots” in \([\text{S II}]\) and \(\text{H}_2\).

\(^4\)IDP3 is publicly available at http://nicmos.as.arizona.edu/software/idl-tools/toollist.cgi
The high angular resolution NICMOS 2.12\(\mu\)m continuum subtracted image and a comparison of the \(\text{H}_2\) emission with that of \(\text{H}\alpha\) and \([\text{S II}]\) from the WFPC2 camera, are displayed in Figure 2. These images show that, in detail, the atomic and NIR \(\text{H}_2\) gases have more complex morphologies than those that can be described in terms of simple “bullets” or “knots”. The gross properties of the emission from both gases have been discussed in some detail by Hartigan, Curiel and Raymond (1989), and so we will concentrate on two of the most interesting and relatively new features: the \(\text{H}_2\) jet in SVS 13 and the HH 7 WS.

### 3.1. \(\text{H}_2\) Jet in SVS 13

An enlargement of the NICMOS image around the SVS 13 source shows (Figure 3) the presence of highly collimated and resolved \(\text{H}_2\) emission, with a relatively high flux density that we identified with a small jet. The brightest component of the jet has 1.\"24 in length at \(\text{PA} = 163^\circ\) (although fainter emission extends up to 2.\"4). The NICMOS image therefore resolves and confirms that the 2.\"6 asymmetric feature arising SE of SVS 13, detected in recent \(\text{H}_2\) Fabry-Perot (F-P) observations by Davis et al. (2002), corresponds indeed to a small-scale jet. At a distance of 350pc, the jet has a length of 430 AU, making it one of the smallest \(\text{H}_2\) jets known. The subtracted PSF SVS 13 image has a small “bump” in the North aligned with the jet and could be tracing the counter-jet. The jet itself is narrower close to the source with an aspect ratio of \(\sim 2.2\), and becomes wider at \(\sim 0.64\) (222 AU) from SVS 13. Considering that we are looking at this outflow in projection, at approximately 30\(^\circ\) with respect the plane of the sky (Herbig & Jones 1983), the structure of this jet is remarkably similar to that of DG Tau, the best example of an optical micro-jet (Solf & Böhm 1993; Kepner et al. 1993; Lavalley et al. 1997; Lavalley-Fouquet, Cabrit & Dougados 2000; Dougados et al. 2000).

The presence of an \(\text{H}_2\) jet is consistent with other molecular tracers of high velocity gas. For example, high-sensitivity interferometric CO J=2-1 observations show already a “bridge” of gas between SVS 13 and the rest of the outflow, including a jet-like feature in the ‘extremely-high-velocity’ (EHV) gas near the source (Bachiller et al. 2000). The CO J=2-1 gas has a peak radial velocity of \(\sim -172\) km s\(^{-1}\), similar to that of \(-175 \pm 50\) km s\(^{-1}\) observed in \([\text{S II}]\) 6717/31 in HH 11, the nearest knot to SVS 13 (Solf & Böhm 1987). And finally, high spectroscopic resolution observations at 2.12\(\mu\)m by Davis et al. (2001) clearly show two velocity components in the \(\text{H}_2\) gas within 1\" of the source, with a blueshifted high velocity component of \(\sim 100\) km s\(^{-1}\).

One of the interesting things about this jet is that if one assumes a flow velocity of 200 km s\(^{-1}\) for HH 7/11, consistent with the velocity derived from the optical proper motions (Noriega-Crespo & Garnavich 2001), these parameters set a kinematical age of \(\sim 10\) years. SVS 13 became an optically visible source during its last outburst in 1988-90 (Eislöffel et al. 1991; Liseau, Lorenzetti & Molinari 1992), almost 10 years ago, and so is quite possible that the observed jet is the result of such energetic event.

We can compare the \(\text{H}_2\) 2.12\(\mu\)m emission of the bowshock, Mach disk and jet, to have a idea of the
relative physical conditions in these regions. For example, the jet flux density $S_j = 4.1 \pm 0.1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, is three times higher than that of the bowshock, $S_{bs} = 1.4 \pm 0.1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, and ten times higher than that of Mach disk, $S_{md} = 0.4 \pm 0.1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. We can interpret these flux density ratios using the recent spectroscopic results obtained in the far infrared (FIR) with the Infrared Space Observatory (ISO) and molecular shock models (Molinari et al. 2000). HH 7 WS and SVS 13 have similar intensities in the (0-0) S(1)-S(7) H$_2$ pure rotational lines, as well as in other shock indicators like [Ne II] 12.8$\mu$m and [Si II] 34.8$\mu$m, which suggests that a 20-30 km s$^{-1}$ molecular C-shock can explain the NIR and FIR H$_2$ emission in both objects (Molinari et al. 2000). On the other hand, molecular shock models at 20-30 km s$^{-1}$ for Hydrogen densities in the range of $10^4 - 10^5$ cm$^{-3}$ predict that the line intensity of the 2.12$\mu$m line is $\sim 30$ times stronger in the high density models (Kaufman & Neufeild 1996). So to satisfy both ISO observations and theoretical models: (i) the observed flux density ratio $S_j / S_{bs} = 3.1$ requires a higher density for the jet, i.e. that the molecular jet is quite dense after leaving SVS 13, with a Hydrogen gas density of few $\times 10^4 - 10^5$ cm$^{-3}$ (Molinari et al. 2000); and (ii) the bowshock is more dense ($\sim 10^4$ cm$^{-3}$) than the Mach disk.

The presence of an H$_2$ jet ejected from this pre-main sequence source of such small angular scale, explicitly shows that contamination by an outflow in the search for H$_2$ disk systems around young stars is possible, although perhaps not as persistent as these systems become older. For example, the H$_2$ (0-0) S(1) line flux around SVS 13 is $4.0 \pm 0.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, i.e. 5-10 times higher than those found in the T Tauri and Debris-Disk samples of Thi et al. (2001), but certainly comparable to the values detected in their Herbig Ae sample.

### 3.2. HH 7 Working Surface

HH 7 is the leading working surface of the HH 7/11 jet and is perhaps the most characteristic feature of the outflow. An enlargement of the groundbased observations in Figure 4 shows that the H$_2$ emission spatially coexists with that from the atomic gas in both the arc-like bowshock and its Mach disk. Figure 4 also displays the NICMOS and WFPC2 observations of the same region, unfortunately the HST optical images are vignetted, one of the reason why they have not been published before, and so the emission corresponding to the bowshock is missing. The bowshock and Mach disk are separated by $\sim 3.3''$ (1138.5 AU) with peak intensities in H$_2$ at $\alpha(2000) = 3^h29^m08.53$, $\delta(2000) = 31^\circ15'25.5''$ and $\alpha(2000) = 3^h29^m08.31$, $\delta(2000) = 31^\circ15'24.2''$, respectively. The H$_2$ bowshock is large ($\sim 6''$) and subtends a relatively smooth and complete arc of $\sim 140^\circ$. The fact that this shell is not fragmented suggests the presence of a sizeable magnetic field. Theoretical arguments and numerical simulations have shown that a magnetic field can modify the morphology of a jet (e.g. Frank et al. 1998; Stone & Hardee 2000), and that a compressed magnetic field stabilizes a dense gas shell against Rayleigh-Taylor instabilities if $B \sim 10^{-4}$ G (e.g. Blondin, Fryxell & Königl 1990). In our case, if the initial magnetic field is given by $B_0 = n_0^{1/2}10^{-6}$ G, where the preshock density, is $n_0 = 10^4$ cm$^{-3}$, as deduced from the H$_2$ emission, then $B_0 \sim 300 \mu$G. Therefore even a slow shock
of $v_s = 20 \text{ km s}^{-1}$ (consistent with the H$_2$ emission) can compress the magnetic field by a factor 15 ($\sim 0.78 \cdot v_s [\text{km s}^{-1}]$, McKee & Hollenbach 1980), i.e. enough to meet the stability criteria.

In the NICMOS images the H$_2$ emission at the Mach disk is relatively faint (see Figure 4). The high-resolution H$_2$ groundbased observations by Chrysostomou et al. (2000) show a more clear picture of this feature. The presence of a Mach disk in H$_2$ is perhaps more convincing if one uses, for instance, the kinematical information available from F-P observations. At optical and NIR wavelengths, it is possible to distinguish two distinct kinematical components corresponding to the bowshock and the Mach disk separated by $\sim 3'' - 4''$ (Stapelfeldt 1991; Carr 1993; Davies et al. 2001, their Fig. 1). The physical conditions at the Mach disk can be estimated in relative terms by comparing its H$_2$ emission to that of the bowshock. The flux density ratio between the bowshock and Mach disk is 3.5, and this could be due to a slight difference in density and/or shock velocity. Proper motion measurements set an upper limit of 30 km s$^{-1}$ for the velocity of the Mach disk (Noriega-Crespo & Garnavich 2001), which is very close to the predicted shock velocity of the entire working surface. This means that even a complete thermalization of the shock could not account for the observed ratio. If we assume similar pre-shock conditions for the bowshock and the Mach disk, and knowing that Mach disk velocity ($v_{md}$) depends on the jet ($v_j$), bowshock ($v_{bs}$) and pre-shock medium ($v_{med}$) velocities, i.e. $v_{md} = v_j - (v_{bs} + v_{med})$, then it is likely that at the Mach disk the shock velocity itself is less than 20 km s$^{-1}$.

The question is whether or not the H$_2$ emission observed at the Mach disk truly corresponds to that excited by a magnetic precursor (C-shock) or is the result of some other processes, like entrainment or a J-type shock. The detailed answer to this question requires a MHD numerical simulation that is beyond the scope of this paper. The complex interaction of the ion and electron fluids with a magnetic field, coupled with the limited grid resolution of most numerical simulations, could explain why an H$_2$ jet shock or Mach disk has not been seen in recent molecular jet models (e.g. Raga et al. 1995; Suttner et al. 1997)).

One can ask, however, if the conditions at the working surface are the necessary for the development of a magnetic precursor, capable to excite the H$_2$ in the Mach disk. Let’s assume first a 200 km s$^{-1}$ jet flow that generates shock velocities $\sim 100$ km s$^{-1}$. In the most simple scenario (without dust grains) a magnetic precursor needs molecular gas with a low ionization fraction and a moderate magnetic field (Draine & McKee 1993). At the working surface, the bowshock is the first shock that interacts with the surrounding gas, and although a magnetic precursor can excite the gas ahead of the shock, eventually (for shock velocities of $\sim 30 - 50$ km s$^{-1}$) the H$_2$ molecules will be dissociated (Smith 1994; Smith & McLow 1997), except at the ”wings” of the bowshock, where the shocks are oblique and the molecular gas is only excited (Smith 1991; Davis et al. 1999). The emission of the atomic species, e.g. H$\alpha$ and [S II], in the HH7 WS indicates that the postshock gas is partially ionized and warm, and not ideal for a magnetic precursor, as the jet shock encounters this material. The exception could be again at the bowshock wings where the gas recombines more rapidly. This region is indeed where we detect the ‘strongest’ H$_2$ emission at the position of the optical Mach disk. Let’s consider now a lower velocity flow such that the shock velocity is $\leq 50$ km s$^{-1}$. In this case we can
refer to recent results from Lim, Rawling & Williams (2001), where their adaptive grid 2D hydro-code incorporates the chemistry of 102 species, including those for molecules such as H$_2$O or H$_2$. In their three models (A-C), for different jet/environment density ratios, a H$_2$ jet shock is created. For example in their model C, with $n_{\text{jet}} = 50$ cm$^{-3}$ and $n_{\text{env}} = 5$ cm$^{-3}$, the highest H$_2$ density occurs at the Mach disk (Lim, Rawling & Williams 2001; their figure 6).

The above scenarios for the H$_2$ emission at the Mach disk suggest either a fine tuning of the physical conditions of the postshock gas at the working surface to drive a magnetic precursor, or the need to incorporate in the hydrodynamics the entire chemistry network. Perhaps a more straightforward explanation is that a fraction of the H$_2$ gas has been entrained by the jet in its interaction with the molecular ambient medium. This scenario has been recently explored by Raga et al. (2002), where an atomic jet collides sideways with a molecular H$_2$ cloud (see their Fig 1), and as the jet “bounces” from the cloud entrains some of the molecular gas. In practice, there is not need of such strong interaction and is enough for the jet to strike some dense molecular gas along its path, as has been suggested previously for this system (see e. g. Knee & Sandell 2000; Sandell & Knee 2001).

### 3.3. HH 8-11

We have described in the previous two sections what we consider the most outstanding features observed with the high angular resolution NICMOS observations. In this section, we describe briefly the main characteristics in of the other knots HH 8-11 in the H$_2$ 2.12µm and [S II] 6717/31 lines (Figure 5).

**HH 8.** In the WFPC2 images this knot has a filamentary structure that spans $\sim 7''$, with a bright small core ($\sim 2''$) where both the H$_2$ and atomic emission coincide, although with distinct morphologies (Figure 5). Kinematically, the knot follows the overall flow pattern defined by HH 7 and HH 11 (Herbig & Jones 1983; Noriega-Crespo & Garnavich 2001), however, the H$_2$ F-P observations show the molecular gas with a radial velocity of $\sim 40$ km s$^{-1}$ slower than the [S II] gas and with a component at zero and positive velocities (Carr 1993). This suggests that the H$_2$ emission could be either arising from behind the optical object, and is observed in projection (as expected from a bowshock, with a weak shock component at its tail); or could be the result of entrainment at the edge of the cavity created by the jet, but seen also in projection. In both situations, the H$_2$ gas would have a lower velocity than the atomic/ionic gas.

**HH 9.** This knot is not visible in the NICMOS image, which is not a surprise given the short exposure and considering that even in groundbased observations is hard to detect (e. g. Figure 1). At optical wavelengths, the WFPC2 images show a ‘fuzzy’ knot of $\sim 6''$ in size; the knot has a [S II]/H$\alpha$ ratio of $\sim 1.1$ indicating its low excitation (Table 2). HH 9 has a very low radial velocity and essentially zero proper motion (Solf & Bøhm 1987; Noriega-Crespo & Garnavich 2001), so could be either part of the backflow of the jet envelope or an ambient medium condensation that has been excited by the outflow.
HH 10. Already from the groundbased optical images was possible to infer a complex morphology for this “knot” (Figure 1), but certainly not with the detail of the WFPC2 images. The morphology of the [S II] and Hα gas emission are quite similar in shape and span some ∼ 14′′ in the N-S direction while the H2 emission, as in the case of HH 8, is not as extended and well defined (Figure 5).

HH 11. This object is one of the few condensations in the HH 7/11 chain, that at optical wavelengths, looks like a “bullet”. HH 11 is the fastest moving knot of the outflow, with a space velocity in the atomic/ionic gas of 190 km s$^{-1}$ (Noriega-Crespo & Garnavich 2001), and has the highest excitation in the flow (with a [S II]/Hα ratio of ∼ 1.8), indicating shocks as strong as ∼ 60 km s$^{-1}$. Situated at ∼ 10″ from SVS 13, this condensation was probably ejected ∼ 87 yr ago. These properties reinforce the idea that we are witnessing a jet interacting with a moving medium set in motion by a previous ejection event (Raga et al. 1990). The observed H2 emission is located further back from the main object trailing behind the atomic/ionic gas (defined by [S II] and Hα emission), as one expects from the most simple bowshock models which include H2 emission (Smith 1991). Deep groundbased NIR images at 2.12μm show a bit more extended emission in HH 11, but still predominantly behind the optical counterpart (e. g. Chrysostomou et al. 2000). Therefore, HH 11 is most likely to be one of those rare cases where the H2 molecules are dissociated near the stagnation region of the bowshock, but they survive and are excited in those regions where the shocks become weaker (oblique), i.e. at the bowshock wings (Smith 1991).

SVS13 NE. WFPC2 images in [S II] and Hα show a small condensation at approximately 5″ NE of SVS 13, about ∼ 3″ in size (Figure 5), that seems to trace the starting point of an arc-shaped structure north and parallel to the HH 7/11 outflow (see Figure 1). Presently, we don’t have any kinematical information on this knot. But the overall structure reminds us of another well known outflow in L1551, where it has been suggested that the opening angle has changed as a function of time, going from a broad to a narrow configuration (Davis et al. 1995 their figure 9), creating in the process a fan shaped cavity.

4. Conclusions

We have resolved two remarkable features in the molecular Hydrogen emission of the HH 7/11 outflow thanks to HST NICMOS images at 2.12μm: a jet with a length of 430 AU arising from the SVS 13 driving source, and the Mach disk in HH 7, leading working surface. These observations strongly support the presence of small-scale H2 jets arising from Class I/O sources (Davis et al. 2002), and open the possibility that a jet shock can be detected in H2.

Using previously published infrared spectroscopic observations, coupled with molecular shock models, we have determined that: (i) the jet can have a density as high as $10^5$ cm$^{-3}$, for shock velocities of 20-30 km s$^{-1}$, (ii) the magnetic field plays a major role in stabilizing the HH 7 bowshock, (iii) the Mach disk H2 emission is probably produced by shocks of less than 20 km s$^{-1}$; and (iv) the complex distribution of the atomic and molecular gases in HH 7/11, depicted by the NICMOS and
WFPC2 images, coupled with its kinematics, suggests a strong interaction of this outflow with its circumstellar medium.

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REFERENCES

Aspin, C., Sandell, G. Russell, A.P.G. 1994, A&AS, 106, 165
Bachiller, R., Guilloteau, S., Gueth, F., et al. 1998, A&A, 339, L49
Bachiller, R., Gueth, F., Guilloteau, S., Tafalla, M., & Dutrey, A. 2000, A&A, 362, L33
Bally, J., Devine, D., Reipurth, B. 1996, ApJl, 473, 49
Blondin, J.M., Fryxell, B.A., & Königl, A. 1990, ApJ, 360, 370
Böhm, K.H., Solf, J. 1990, ApJ, 348, 297
Carr, J.S. 1993, ApJ, 406, 553, 2000, MNRAS, 314, 229
Chrysostomou, A., Hobson, J., Davis, C.J., Smith, M.D. & Berndsen, A. 2000, MNRAS, 314, 229
Cotera, A. S., Whitney, B. A., Young, E., Wolff, M. J., Wood, K., Povich, M., Schneider, G., Rieke, M., & Thompson, R. 2001, ApJ, 556, 958
Davis, C.J., Mundt, R., Eislöffel, J., & Ray, T.P. 1995, AJ, 110, 766
Davis, C.J., Smith, M.D., Eislöffel, J. & Davis, J.K. 1999, MNRAS, 308, 539
Davis, C.J., Ray, T.P., Desroches, L., Aspin, C. 2001, MNRAS, 326, 524
Davis, C.J., Stern, L., Ray, T.P., & Chrysostomou, A. 2002, A&A, 382, 102
Dougados, C., Cabrit, S., Lavalley, C., & Ménard, F. 2000, A&A, 357, L61
Draine, B. & McKee, C.F. 1993, ARAA, 31, 373
Eislöffel, J., Günther, E., Hessman, F., Mundt, R., Poetzel, R., Carr, J.S., Beckwith, S., & Ray, T.P. 1991, ApJ, L19
Everett, M.E. 1997, ApJ, 478, 246
Frank, A., Ryu, D., Jones, T.W., & Noriega-Crespo, A. 1998, ApJ, 494, L79

Garden, R.P., Russell, A.P.G., Burton, M.G. 1990, ApJ, 354, 232

Gredel, R. 1996, A&A, 305, 582

Herbig, G.H. 1974, Draft Catalog of Herbig-Haro Objects, Lick Obs. Bull. No. 658

Herbig, G.H., Jones, B.F. 1983, AJ, 88, 1040

Kaufman, M.J., & Neufeld, D.A. 1996, ApJ, 456, 611

Knee, L.B.G., & Sandell, G. 2000, A&A, 361, 671

Kepner, J., Hartigan, P., Yang, C., & Strom, S. 1993, ApJ, 415, L119

Lavalley, C., Cabrit, S., Dougados, C., Ferruit, P., & Bacon, R. 1997, A&A, 327, 671

Lavalley-Fouquet, C., Cabrit, S., & Dougados, C. 2000, A&A, 356, L41

Lim, A.J., Rawling, J.M.C., & Williams, D.A. 2001, 376, 336

Liseau, R., Lorenzetti, D. & Molinari, S. 1992, A&A, 253, 119

McKee, C.F., & Hollenbach, D.J. 1980, ARAA, 18, 219

McLeod, B. & Rieke, M.1997, in 1997 HST Calibration Workshop, ed. S. Casertano et al., p. 281

Molinari, S., Liseau, R., & Lorenzetti, D. 1993, A&AS, 101, 5 9

Molinari, S., Noriega-Crespo, A., Ceccarelli, C. et al. 2000, ApJ, 538, 698

Noriega-Crespo, A., & Garnavich, P.M. 2001, AJ, 122, 3317

Raga, A.C., Binette, L., Canto, J., & Calvet, N. 1990, ApJ, 364, 601

Raga, A.C., Taylor, S.D., Cabrit, S., & Biro, S. 1995, A&A, 296, 833

Raga, A.C., de Gouveia dal Pino, E., Noriega-Crespo, A. Velázquez, P.F. & Mininni, P. 2002, A&A (in press).

Reipurth, B. & Bally, J. 2001, ARAA, 39, 403

Sandell, G., & Knee, L.B.G. 2001, ApJ, 546, L49

Smith, M.D. 1991, MNRAS, 252, 378

Smith, M.D. 1994, MNRAS, 266, 238

Smith, M.D. & MacLow, M.-M. 1997, A&A, 326, 801

Solf, J., & Böhm, K.H. 1987, AJ, 93, 1172
Solf, J., & Böhm, K.H. 1993, ApJ, 410, L31

Stapelfeldt, K.R. 1991, PhD Thesis, California Institute of Technology

Stapelfeldt, K.R., Scoville, N.Z., Beichman, Ch.A., Hester, J.J., & Gautier, T.N., III 1991, ApJ, 371, 226

Stobie, E., Lytle, D., Barg, I., & A. Ferro, 1999, in proceedings of the NICMOS and the VLT Workshop held in Pula, Sardinia, Italy May 26-27 of 1998. Editors Freudling, W. & Hook, R. p. 77

Stone, J.M., & Hardee, P.E. 2000, ApJ, 540, 192

Strom, S.E., Vrba, F.J., & Strom, K.M. 1976, AJ, 81, 314

Suttner, G., Smith, M.D., Yorke, H.W., & Zinnecker, H. 1997, A&A, 318, 595

Thi, W.F., van Dishoeck, E.F., Blake, G.J. et al. 2001, ApJ, 561, 1074

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| Instrument | Camera | Date    | Filter        | Exposure (sec) |
|------------|--------|---------|---------------|----------------|
| NICMOS     | NIC2   | 09 Jan 98 | F187N, F204, F212N | 80, 80, 160    |
| WFPC2      | · · ·  | 18 Oct 98 | F656N, F673N  | 3600, 3600     |
Table 2. Fluxes by Region

| Region | $H_2$ (F212N) | $H\alpha$ (F656N) | [(S II)] |
|--------|---------------|-------------------|---------|
|        | Flux          | Area              | Flux/Area | Flux          | Area  | Flux/Area |
|        | ($\times 10^{-14}$) | ($\times 10^{-15}$) | ($\times 10^{-18}$) | ($\times 10^{-18}$) | ($\times 10^{-18}$) | ($\times 10^{-19}$) |
| HH 7   | 36.3±0.2      | 50.1              | 7.3      | 4.78±0.01 | 80.6  | 0.59      | 13.74±0.02 | 80.6  | 1.7       |
| HH 7$^d$ | ...           | ...               | ...      | 0.74±0.01 | 4.2   | 1.76      | 2.85±0.01 | 4.2   | 6.8       |
| HH 8   | 6.2±0.2       | 30.0              | 2.1      | 3.12±0.01 | 26.5  | 1.18      | 2.81±0.02 | 26.5  | 1.1       |
| HH 9   | ...           | ...               | ...      | 0.84±0.01 | 19.6  | 0.43      | 3.53±0.01 | 19.6  | 1.8       |
| HH 10  | 6.4±0.2       | 36.8              | 1.8      | 3.11±0.01 | 40.9  | 0.76      | 8.24±0.02 | 40.9  | 2.0       |
| HH 11  | 3.0±0.2       | 22.7              | 1.3      | 2.91±0.01 | 12.2  | 2.39      | 5.27±0.01 | 12.2  | 4.3       |

$a$ erg s$^{-1}$ cm$^{-2}$

$b$ arcsec$^{-2}$; errors for the derived area are ±0.02

$c$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$

$d$ Data for the F673N and F656N emission associated with a small area encompassing just the Mach disk
Fig. 1.— Groundbased images of HH 7/11 outflow (at the same scale) in [S II] 6717/31 Å (top) and H$_2$ 2.12μm (bottom). There is a one-to-one correspondence for each of the main objects, even for HH 9 which is quite faint in H$_2$.

Fig. 2.— (top) NICMOS continuum subtracted grayscale image at H$_2$ 2.121μm (F212N) of the HH 7/11 outflow. (bottom) Combined false three color image of HH 7/11. Red is F212N (H$_2$), green is F673N ([S II] 6717/31 Å), and blue is F656N (Hα).

Fig. 3.— Continuum and PSF subtracted grayscale F212N image of SVS 13 and its jet arising at the South. The overlayed F212N contours correspond to 1.2, 1.7, 2.2, 2.8, 3.4, 3.9, 9.5, and 15.1×10$^{-19}$ W m$^{-2}$

Fig. 4.— (left) A comparison of the groundbased observations of HH 7 working surface in H$_2$ at 2.12μm (grayscale) and [S II] 6717/31 Å (white contours), which shows the spatial coexistence of the atomic and molecular emission. (right) A contour map of NICMOS and WFPC2 observations of HH 7, with H$_2$ at 2.12μm (black) and [S II] 6717/31 Å (red). The sharp edge of the [S II] emission is due to vignetting of the WFPC2 image (see Fig. 1). The location bowshock and Mach disk are marked. H$_2$ contour levels are 0.3, 0.5, 0.7, 0.8, 1.1, 1.3, 1.5, 1.7, 1.9, 2.1, 2.2 and 2.5×10$^{-19}$ W m$^{-2}$.

Fig. 5.— In all 4 figures black contours are H$_2$ (F212N), red are [S II] (F673N), and the data have been boxcar smoothed with a 3×3 pixel kernel size to improve their quality. (From the top left) **HH 8 map.** Contour levels for H$_2$ are 1.5, 2.2, 2.9, 3.6, 4.4, 5.1, 6.5, 7.8, 9.2, 10.5, 11.9, 13.3, 14.6 and 16.0×10$^{-20}$ W m$^{-2}$. Contour levels for [S II] are 0.67, 0.84, 1.0, 1.2, 1.35, 1.5, 1.7, 1.85, 2.3, 2.0, 7.0, 3.1, 3.5, 3.95, 4.4 and 4.8×10$^{-26}$ W m$^{-2}$. **HH 10 map.** Contour levels for H$_2$ are 1.5, 1.9, 2.3, 2.7, 3.0, 3.4, 3.8, 4.2, 4.6, 4.9 and 5.3×10$^{-20}$ W m$^{-2}$. Contour levels for [S II] are 0.88, 1.2, 1.6, 1.9, 2.3, 2.6, 3.0, 3.3, 3.7, 4.0, 4.4, 4.7 and 5.1×10$^{-26}$ W m$^{-2}$. **HH 11 map.** Contour levels for H$_2$ are 0.6, 1.0, 1.5, 1.9, 2.3, 3.0, 3.7, 4.4, 5.1 and 5.8×10$^{-20}$ W m$^{-2}$. Contour levels for [S II] are 0.4, 0.8, 1.1, 1.5, 1.8, 2.2, 2.5, 2.8, 3.2, 3.5, 3.9, 4.2, 4.6 and 4.9×10$^{-20}$ W m$^{-2}$ **NE of SVS13 map.** Contour levels range from 0.3 to 44×10$^{-26}$ W m$^{-2}$ for Hα and 0.1 to 26×10$^{-26}$ W m$^{-2}$ for [S II], where the largest values pertain to the brightest contours of SVS 13.
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