HIGH SPECTRAL RESOLUTION H₂ MEASUREMENTS OF HERBIG-HARO OBJECTS 38, 46/47, AND 120

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ABSTRACT

We report high spectral resolution (R ≈ 20,000) measurements of the H₂ 1–0 S(1) line in Herbig-Haro objects 38, 46/47, and 120. The long-slit spectra reveal complex velocity structure with evidence for bow-shock structures, as well as prompt entrainment and shock heating of ambient molecular gas. Individual knots within HH 38 show distinct double-peaked velocity structure, consistent with that expected from spatially unresolved bow shocks. A portion of the HH 47A bow shock is resolved in our measurements, and the kinematics of the H₂ trace closely that found for Hα emission. The evidence indicates that the preshock medium for HH 47A that formed in the wake of a previous ejection contains molecular clumps. The HH 46C jet A feature in the HH 46/47 counterflow is suggestive of a bow shock emerging from near the base of the flow, with H₂ emission arising from ambient cloud material excited in the oblique flanks of the bow shock. HH 46F is situated downstream at the boundary between the ovoid cavity and the ambient cloud material, and represents either entrainment by a stellar wind that fills the cavity or entrainment in the far wing of a giant bow shock. For HH 120, the H₂ velocity results also corroborate those found from atomic emission, and there is substantial evidence that the preshock medium is inhomogeneous, producing clumps of H₂ emission on the wings of a bow shock that has an apex at HH 120A.

Key words: ISM: Herbig-Haro objects — ISM: jets and outflows

1 INTRODUCTION

The role played by Herbig-Haro (H-H) objects and jets from young stellar objects (YSOs) in driving the more widespread bipolar molecular flows observed in CO has been the target of recent investigations (Davis et al. 2002; Davis 2002). The use of high-resolution spectroscopic instruments in the near-infrared has advanced our understanding of the role of molecular hydrogen emission as a possible intermediate manifestation of the coupling between the atomic outflows and the much cooler CO outflows. Long-slit echelle observations and Fabry-Pérot imaging have revealed the dynamics and kinematics of a number of H-H jets and shock structures. Davis et al. (2000) used echelle spectra to investigate the shock structures of a number of H-H objects, finding evidence for turbulent boundary layers and entrainment of material to form massive bipolar molecular outflows. Schwartz & Greene (1999) used near-IR echelle spectroscopy to investigate the dynamics and kinematics of HH 43. Mousessian et al. (2000) have applied Fabry-Pérot techniques to reveal the structure and dynamics of the HH 7-11 system. Observations of near-infrared H₂ emission have the additional advantages of suffering less extinction than optical observations in the dark cloud complexes, where most of the H-H flows are located, and serving as probes to the molecular bulk of the flow material, thus permitting a more complete picture of outflow systems.

2 OBSERVATIONS AND DATA REDUCTION

The NASA 3.0 m Infrared Telescope equipped with CSHELL, the single-order Cryogenic Echelle Spectrograph (Tokunaga et al. 1990; Greene et al. 1993), was used on the nights of 1996 January 8 and 9 to obtain spatially resolved spectra of structures in HH 38, HH 46/47, and HH 120. Spectra of the H₂ 1–0 S(1) emission line were acquired with a 1" (5 pixel) wide slit, yielding a spectral resolution of about 21,000 (14 km s⁻¹). The detector was a 256 × 256 pixel InSb array, and order sorting was accomplished with the use of stock circular variable filters (CVFs). The slit length was 30" with an image scale of about 0′′2 pixel⁻¹.

In order to locate slit positions, direct images of each H-H object were first obtained in the 1–0 S(1) line of H₂ with 30 s exposures on target followed by 30 s sky exposures. Owing to the small field of view and vignetting in the CVF system, the extended structure of HH 38 could not be obtained with a single exposure. Consequently, three exposures, offset from one another by about 10′′, were required to reveal the extended structure and to locate appropriate positions for slit placement. Spectra at each position involved single 400 s exposures on target followed by 400 s sky exposures.

An early-type standard (HR 1666) was observed at eight positions along the slit to assess telluric absorption and to measure the degree of interference fringing caused by internal reflections in the substrate cavities of the CVFs. As discussed in Schwartz & Greene (1999), no telluric absorption was found in the vicinity of the 1–0 H₂ emission line, and the fringe amplitudes were found to be about 10% of the signal in the dispersion direction with a
smaller variation along the slit as well. Full-slit lamp spectra were used to obtain field distortion corrections through use of the GEOTRAN task in IRAF. The data reduction followed the procedure discussed in Schwartz & Greene (1999). Measurements of seven telluric absorption lines in the spectra of standard stars agreed to within about 3 km s\(^{-1}\) with the Solar Atlas (Kurucz et al. 1984) values.

Approximate flux calibrations for the H\(_2\) emission were obtained from observations of the standard stars HR 1666 and HR 1855. Based upon the seeing profile of the standard stars, it is estimated that only about 70\% of the light from the stars entered the 1\" slit, so the H\(_2\) fluxes have been scaled upward by 30\%. Given the uncertainties due to fringing, the use of point sources (standard stars) to calibrate diffuse sources, and atmospheric extinction, we estimate that the H\(_2\) fluxes have uncertainties from 30\% to 50\%.

3. DATA ANALYSIS

To delineate the portions of each of the objects observed, gray-scale images have been formed from the restricted direct field of CSHELL. The images, obtained in the 1–0 S(1) line of H\(_2\), are displayed in the left panels of Figures 1 (HH 38), 2 (HH 47A), 3 (HH 46C jet), 4 (HH 46F), and 5 (HH 120). Next to each direct image panel is a drawing that indicates the orientation of the image and the direction to the exciting star. The slit position and width is drawn with dashed lines on the direct image and labeled in arcseconds to correlate with the position-velocity (p-v) panels. The H\(_2\) flux levels for the lowest contour and the linear contour interval fluxes are given in the figure captions. We emphasize that the direct images were taken only for the purpose of identifying features for spectroscopy. With generally poor signal-to-noise ratio, the images do not show the detailed morphologies apparent in other H\(_2\) imaging studies, such as those of

**Fig. 1.**—Restricted direct H\(_2\) image of HH 38 and the p-v diagrams for HH 38. The slit positions are indicated on the direct image and labeled according to position in the p-v diagrams. The orientation of the direct image and the direction to the exciting star are indicated next to the direct image. For knot A, the lowest contour is at a flux level of 1.0 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) \AA\(^{-1}\), with a linear contour interval of 1.2 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) \AA\(^{-1}\). For knot B, the lowest contour is at flux level 8.7 \(\times\) 10\(^{-6}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) \AA\(^{-1}\), with a contour interval of 2.3 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) \AA\(^{-1}\). For knot C, the lowest contour is at the same flux level as knot B, but with a contour interval of 2.6 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) \AA\(^{-1}\).
Eisloffel et al. (1994) on HH 46/47, Hodapp & Ladd (1995) on HH 120, and Stanke, McCaughrean, & Zinnecker (2000) on the HH 38/43 system.

Velocity measurements of the emission knots indicated in Figures 1–5 were extracted using a 100 (5 pixel) section of the slit centered upon each knot. For the knots with sufficient signal-to-noise ratios, the observed line profiles were deconvolved with the instrumental line profiles that possessed a full width at half-maximum (FWHM) of 12.7 km s\(^{-1}\), as determined from the arc lamp lines. Because the deconvolution assumed that the line profiles can be approximated by Gaussian profiles, and because asymmetries are clearly apparent in some of the observed profiles, one should use the velocity dispersion measures only as an indicator of the velocity spread in individual knots. In HH 38 and HH 46C jet A, high- and low-velocity components are clearly

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**Fig. 2.**—Same as Fig. 1, but for HH 47A. The flux level of the lowest contour is 1.4 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Å\(^{-1}\), and the linear contour interval is 1.1 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Å\(^{-1}\).

**Fig. 3.**—Same as Fig. 1, but for HH 46C jet. The flux level of the lowest contour is 1.1 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Å\(^{-1}\), and the linear contour interval is 1.0 \(\times\) 10\(^{-5}\) ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) Å\(^{-1}\).
resolved. For HH 120A and HH 120B, the observed asymmetric profiles were deconvolved assuming the presence of two Gaussians at each position. Although fits of comparable goodness were possible by using three or more Gaussians, as is the case with virtually any asymmetric profile, within the uncertainties of the fits, the two-Gaussian fits represent the simplest possible analysis. Table 1 lists the heliocentric radial velocities for each knot, and the FWHM of the emission lines associated with the knots. Position-velocity plots for each of the slit positions are shown as contour diagrams in Figures 1–5. In Figure 5, one can note the position-velocity structure associated with knot A that

Fig. 4.—Same as Fig. 1, but for HH 46F. The flux level of the lowest contour is $1.2 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Å$^{-1}$, and the linear contour interval is $1.0 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Å$^{-1}$.

Fig. 5.—Same as Fig. 1, but for HH 120. IRS 4 is the exciting source for HH 120. The flux level of the lowest contour is $1.2 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Å$^{-1}$, and the linear contour interval is $3.4 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Å$^{-1}$.
appears to consist of a high-velocity ($-39.4 \text{ km s}^{-1}$) feature and a weak low-velocity ($-5.0 \text{ km s}^{-1}$) feature that is offset spatially by about 0"5 toward knot B. Knot B exhibits an asymmetry in the sense of having an extended blue wing. The two-Gaussian deconvolution of knot A yielded a flux ratio of 2.0 for the $-39.4 \text{ km s}^{-1}$ feature compared with the $-5 \text{ km s}^{-1}$ feature, and for knot B the ratio was 3.0 for the $4.3 \text{ km s}^{-1}$ feature compared with the $-13 \text{ km s}^{-1}$ feature.

4. DISCUSSION

4.1. HH 38

Surprisingly little work has been done on HH 38 since its discovery by Haro (see Herbig 1974). Cohen & Schwartz (1983) associated it with the flow responsible for HH 43 upon the basis of an approximate alignment of HH 43 and HH 38 with the putative exciting star (HH 43 IRS 1) that was discovered with infrared mapping to be located about 1' to the northwest of HH 43. Gredel (1994) later discovered that the putative exciting star is a binary. More recently, Stanke et al. (2000) have reported infrared H$_2$ imaging of the region that reveals a long string of H-H objects (including HH 38, HH 43, and HH 64) aligned with a recently discovered far-IR/millimeter source (HH 43 MMS 1) that is almost certainly the exciting star for the system. The new source is located about 3' northwest of HH 43 IRS 1 and shows the signatures of a class 0 protostellar source. The Stanke et al. (2000) image reveals an independent flow from HH 43 IRS 1 that produces a faint bow shock northwest of the star, but which is not in the alignment of the HH 38, 43, and 64 system. Eisloeffel & Mundt (1997) present an optical [S ii] image of the HH 38/43 region that reveals multiple knot structure in HH 38 that appears to correlate with the H$_2$ structure seen in Stanke et al. (2000), but with the northernmost structure (our knots A and B) appearing relatively fainter than in H$_2$. The IR image of Stanke et al. (2000), taken in 1998, shows knot B to be somewhat fainter than in our image, and a knot is also seen immediately to the south of our knot C, which is outside the restricted field of our direct image. Optical spectra of HH 38 obtained by M. A. Dopita, R. D. Schwartz, & M. Cohen (1981, unpublished) show that the optical knots are of low excitation with the [S ii] emission intensity rivaling that of H$_2$, and [N i] $\lambda 5200$ emission appears comparable to the H$\beta$ emission intensity. The assumed distance to the HH 38/43 complex is 450 pc (Stanke et al. 2000).

The position-velocity diagrams for three knots in HH 38 (Fig. 1) reveal double-line features expected in bow shocks. Davis et al. (2000) find similar features in HH 7 and HH 33. In the case of HH 38, the weak feature at higher negative velocity is most likely identified with emission closer to the apex of a bow shock that has been swept nearly to the jet speed. By contrast, emission from the wings of the bow shock will be dominated by ambient gas that has undergone little acceleration through the oblique bow wave. Much of the ambient H$_2$ is evidently dissociated at the bow shock apex, resulting in relatively weak emission. However, due to the much lower shock velocities in the oblique wings of the bow shock, the post shock temperatures are insufficient to dissociate a large fraction of the H$_2$, leading to stronger emission. An argument against the identification of the high-velocity peaks with the apex of a bow shock could be made upon the basis of the small velocity dispersions in those features. Divergence of post shock flow at the apex should yield considerably broader lines than in the wings of the bow shock. We note, however, that there is considerable uncertainty associated with the line width measurements of the weak high-velocity features. The velocity measurements in Table 1 indicate that the separations of the two velocity components are about 45, 47, and 54 km s$^{-1}$ for knots A, B, and C, respectively. This suggests that the shock velocity at the apex may be $\geq 50 \text{ km s}^{-1}$.

The negative velocities seen in HH 38 are consistent with an object that has been ejected toward the foreground of a dark cloud that harbors the exciting star. It is curious, however, that HH 43, situated between the exciting star and HH 38, shows small positive heliocentric velocities (3 km s$^{-1} \leq v \leq 24$ km s$^{-1}$), suggestive of motion predominantly in the plane of the sky (Schwartz & Greene 1999). Stanke et al. (2000) suggest that the motion of the H-H objects in this system is primarily in the plane of the sky, as evidenced by the absence of a detectable bipolar CO flow. It seems unlikely that the precessional motion suggested for the components of HH 43 by Schwartz & Greene (1999) could give rise to the velocity discrepancy between HH 38 and HH 43. It would be of considerable interest to obtain optical emission-line velocities for all of the H-H objects in this flow and to confirm their expected motions away from the source HH 43 MMS 1 with proper-motion measurements.

4.2. HH 46/47

The HH 46/47 system, discovered by Schwartz (1977), is the prototype system for isolated star formation in a Bok Globule. The globule (ESO 210-6A) harbors an embedded young binary system of 0"26 separation and component luminosities of about 5 and 7 $L_\odot$ (Reipurth et al. 2000). The distance to this system has been estimated variously at 350 (Eisloeffel et al. 1994) to 450 pc (Graham & Heyer 1989). A bipolar jet emanates from one of the components with the blueshifted visible jet flow to the northeast in the foreground of the globule. Infrared observations reveal the redshifted counterflow penetrating through the globule to its...
backside, where bow shocks associated with the flow can be seen optically as they emerge in projection from behind the globule. The system has been studied in exquisite detail with *Hubble Space Telescope* (*HST*) imaging of the visible flow (Heathcote et al. 1996) and infrared $H_2$ imaging of the entire system (Eisloeffel et al. 1994). Our study focuses upon three discrete components of the flows: $HH 47A$, a bright bow shock at the terminus of the blueshifted optical jet; $HH 46C$ jet, the redshifted counter jet proximate to the exciting star; and $HH 46F$, located at the boundary of a cavity formed by the redshifted flow inside the globule.

4.2.1. $HH 47A$

The first detection of $H_2$ emission in $HH 47A$ was by Schwartz (1983) with the identification of six fluorescent ultraviolet emission lines produced by $Ly\alpha$ pumping of $H_2$ molecules, which in turn must first be warmed to the second vibrational state of the ground electronic state. The $B-X$ (1, 3), (1, 6), (1, 7), and (1, 8) transitions were observed in the wavelength range $\lambda\lambda 1250-1565$ Å. The expected near-infrared (NIR) $H_2$ quadrupole emission in $HH 47A$ was first detected by Wilking et al. (1990), and the NIR $H_2$ emission was mapped out in detail for the $HH 46/47$ system by Eisloeffel et al. (1994). Curiel et al. (1995) employed *HST* ultraviolet imaging and spectroscopy to investigate the emission from $HH 47A$, confirming the presence of the $B-X$ lines produced by $Ly\alpha$ fluorescence and showing that a dominant portion of the continuum UV emission is due to two-photon emission from neutral hydrogen. Heathcote et al. (1996) have presented a detailed analysis of optical *HST* images of the $HH 47$ flow, and Hartigan et al. (1999) have focused upon the optical structure and the UV/optical spectra of $HH 47A$. Micono et al. (1998) have reported proper-motion measurements of $H_2$ features in the system. The $H_2$ knots for which there are visible counterparts show approximately the same proper motions as the visible knots, as measured by Eisloeffel & Mundt (1994).

An unanswered question in previous studies is that of the relation of the optical emission seen in atomic lines to that of the NIR $H_2$ emission in $HH 47A$. The registration of $H_2$ and $[S\,\text{II}]$ images by Eisloeffel et al. (1994) shows that the peak $H_2$ emission is located at the bow shock, but is displaced about 2" to the west of the apex of the bow shock along the northern wing of the shock. The image reveals $H_2$ emission outlining faintly the opposite wing of the bow shock to the southeast, with very faint emission elsewhere over the $HH 47A$ complex. The high spectral resolution $H\alpha$ measurements of $HH 47A$ reported by Hartigan, Raymond, & Meaburn (1990) were obtained with a slit in position angle 57° aligned along the jet, whereas our 90° slit orientation captured only the peak $H_2$ emission along the northern bow shock wing. One of the two parallel slit positions used by Hartigan et al. (1990) appears to pass through the approximate position of the peak $H_2$ emission. The $H_2$ heliocentric velocity at the $H_2$ peak position is seen to be about $-79$ km s$^{-1}$ in the position-velocity diagram of Hartigan et al. (1990). This agrees closely with the velocity of $-76.5$ km s$^{-1}$ determined from our $H_2$ measurements and suggests that the $H_2$ emission indeed arises from postshock gas. A second slit position used by Hartigan et al. (1990) was offset 4" to the south, passing through the region of the Mach disk and closer to the apex of the bow shock, where the $H\alpha$ emission is stronger, and where the heliocentric velocity is centered near $-105$ km s$^{-1}$. The velocity structure revealed by the optical data are fully consistent with the bow shock model for $HH 47A$ developed in more detail by Hartigan et al. (1999).

The optical data differ from the infrared data by showing a larger velocity dispersion ($\sim 60$ km s$^{-1}$ FWHM estimated for $H\alpha$) than the $H_2$ emission (19 km s$^{-1}$ FWHM). It is possible that the atomic emission is weighted more by brighter $H\alpha$ emission in the region of the apex where the velocity dispersion would be expected to be greater due to postshock flow divergence. In addition, atomic emission would suffer additional thermal broadening and possibly broadening due to charge exchange. The ideal case of the working surface of a jet involves jet gas, which passes through the Mach disk and then is directed backward along the side of the jet in a shocked cocoon. The shocked cocoon is separated from the bow shock gas by a cooling layer that prevents mixing of the bow shock and Mach disk gases. Numerical calculations, however, have shown that the cooling layer is subject to instabilities, and the Mach disk and bow shock gases can undergo complex mixing as the cooling layer experiences fragmentation. The fragmentation of the cooling layer in $HH 47A$ is clearly indicated in the $[S\,\text{II}]$ and $H\alpha$ *HST* images of Hartigan et al. (1999). The continuum ultraviolet *HST* images of $HH 47A$ (Curiel et al. 1995) show a close morphological correspondence to the optical images. This is not surprising since the ultraviolet emission is dominated by two-photon emission from neutral hydrogen that should trace the same emission pattern as $H\alpha$. The $H_2$ ultraviolet fluorescence could arise from molecules mixed with the atomic gas, or from the region of peak NIR $H_2$ emission if sufficient $Ly\alpha$ flux reaches the northern wing of the bow shock.

The location of the peak NIR $H_2$ emission and the kinematics of the $H_2$ gas support the contention of Morse et al. (1994) that the molecular emission in $HH 47A$ is caused by the presence of $H_2$ molecules in the wake of $HH 47D$ into which the $HH 47A$ jet is propagating. Evidently, these molecules either survived the passage of the $HH 47D$ shock, or were produced by reformation in the wake of $HH 47D$. In either case, the molecules were swept to a velocity of about $210$ km s$^{-1}$ with respect to the exciting star if one adopts the model of Hartigan et al. (1999), where the angle of the flow with respect to the plane of the sky is $34^\circ$ (Eisloeffel & Mundt 1997). Moreover, as pointed out by Morse et al. (1994), the preshock $H_2$ must experience shielding from ionizing radiation of the Gum Nebula, since both $HH 47A$ and $HH 47D$ appear to have moved beyond the rim of the globule into the ionizing field of the Gum Nebula. The structure of the $H_2$ emission further suggests that the gas in the wake of $HH 47D$ (the $HH 47A$ preshock gas) is inhomogeneous, as might be expected if $H_2$ reformation occurred in denser postshock fragments after passage of the $HH 47D$ shock.

Finally, it can be noted in the position-velocity diagram for $H_2$ in $HH 47A$ (Fig. 2) that a velocity gradient occurs ranging from $-77$ km s$^{-1}$ at peak emission to about $-94$ km s$^{-1}$ at east along the bow shock near the apex. This agrees with the $H\alpha$ velocity at the apex seen in Hartigan et al. (1990) and is expected of bow shock kinematics where the maximum acceleration of material occurs at the apex of the bow shock, with smaller acceleration along the oblique wings of the bow shock. Relative to the cloud that has $v_{\text{helio}} = 21.9$ km s$^{-1}$, according to Kuiper et al. (1987), the radial velocity of the apex is about $-132$ km s$^{-1}$. With the
proper motion of 182 km s\(^{-1}\) for the apex reported by Eisloeffel & Mundt (1994), we compute an inclination to a sky plane at the rest velocity of the cloud of about 36°.

### 4.2.2. HH 46 Counterjet

The H\(_2\) image of the HH 46 counterflow seen in Eisloeffel et al. (1994) suggests that the narrow counterjet emerges at the base of an ovoid cavity that has been excavated in the globule by a stellar wind or previous episodic flows from the exciting star. In their proper-motion study of the counterjet, Micono et al. (1998) identify the jet as HH 46C jet, and we adopt their nomenclature for the identification of knots in the jet. The [S\(_{\text{ii}}\)] images seen both in Reipurth & Heathcote (1991) and in Eisloeffel et al. (1994) show a similar morphology, but with diffuse [S\(_{\text{ii}}\)] emission surrounding a larger portion of the sharply defined counterjet. Reipurth & Heathcote (1991) have secured high-dispersion optical spectra of this region of the counterflow, finding a nearly constant velocity for the jet (\(v_{\text{helio}} \approx +111\) km s\(^{-1}\)), but a decelerating velocity from about 111 km s\(^{-1}\) near the base of the jet to about 50 km s\(^{-1}\) downstream for the diffuse [S\(_{\text{ii}}\)] component. It is suggested that the diffuse decelerating flow is due to the interaction of a stellar wind with cavity walls.

Our data (Fig. 3) exhibit a striking bifurcation of the H\(_2\) velocity between the “base” of the jet and the jet itself, a feature that is seen in the low-dispersion H\(_2\) spectra of Eisloeffel, Smith, & Davis (2000). The diffuse structure (HH 46C jet A) that we refer to as the “base” of the jet exhibits \(v_{\text{helio}} = 31.6\) km s\(^{-1}\). This is only about 10 km s\(^{-1}\) greater than the velocity of the parent cloud (and presumably the velocity of the exciting star) found by Kuiper et al. (1987) to be \(v_{\text{helio}} = 21.9\) km s\(^{-1}\). There is also faint H\(_2\) emission in this diffuse knot at the jet heliocentric velocity of about 116 km s\(^{-1}\). Although it is not clearly evident in the position-velocity contour diagram (Fig. 3), in the original spectrum there is a hint of faint emission connecting the low- and high-velocity features at the base of the jet.

In combination with the detailed high-resolution optical spectra of the HH 46C jet obtained by Reipurth & Heathcote (1991) and the proper motion study of the HH 46C jet by Micono et al. (1998), our data are difficult to interpret in terms of a coherent model. First, we see no evidence for a diffuse decelerating component along the jet as seen in [S\(_{\text{ii}}\)] by Reipurth & Heathcote (1991). The [S\(_{\text{ii}}\)] deceleration is best seen in the Reipurth & Heathcote (1991) spectrum, which was obtained with a slit position off the axis of the jet, but cutting through the diffuse emission to the northwest of the jet. Although it is possible that our spectrum was not deep enough to uncover this faint diffuse component, one can note in the H\(_2\) and [S\(_{\text{ii}}\)] images of Eisloeffel et al. (1994) that indeed the [S\(_{\text{ii}}\)] emission appears to surround a larger portion of the jet than the H\(_2\) emission that appears to be more confined to the smaller diffuse structure of HH 46C jet A. Because of bright overlying [S\(_{\text{ii}}\)] emission from the Gum Nebula at the approximate velocity of the cloud, it is not possible to determine from the Reipurth & Heathcote (1991) spectra whether the “base” of the jet exhibits a [S\(_{\text{ii}}\)] feature, which would correspond to the bright low-velocity feature that we see in H\(_2\) (Fig. 3). It is possible that the low-velocity H\(_2\) component is due to highly oblique shocks in dense material that is located at or near the orifice where the flow opens into the ovoid cavity. The low velocity, however, suggests that it is the ambient cloud material that is being shocked, perhaps through prompt entrainment, and accelerated to about 10 km s\(^{-1}\) relative to the cloud. The [Fe \(_{\text{ii}}\)] and H\(_2\) spectra of the counterjet reported by Fernandes (2000) suggest that the jet base feature could be the result of the most recent episodic ejection. Fernandes finds strong infrared [Fe \(_{\text{ii}}\)] emission in the feature at the velocity (\(v_{\text{helio}} \approx 100\) km s\(^{-1}\)) of the jet. Therefore, the high-velocity [Fe \(_{\text{ii}}\)] emission could represent the head of a bow shock, where most of the H\(_2\) is dissociated, with the lower velocity H\(_2\) emission arising from the wings of the bow shock, where molecular material is being entrained as the latest ejection of a confined jet opens into the ovoid cavity.

A remaining mystery is that of the proper motion of 136 km s\(^{-1}\) reported for the H\(_2\) image of HH 46C jet A by Micono et al. (1998). Our spectra indicate that the flux from this feature is dominated by the low-velocity H\(_2\) component. Therefore, the velocity and proper-motion data do not yield a space velocity for the feature that is commensurate with the jet itself. Taken at face value, the space velocity would indicate a flow inclination to the sky of only 4° for knot A (relative to a plane in the rest frame of the cloud). Although the proper motions of the jet knots B and D are uncertain, if we use the best proper-motion measurement, which is for knot D (\(v = 229\) km s\(^{-1}\)), and a radial velocity of 92 km s\(^{-1}\) to the cloud (from our measurements, we find an inclination angle of about 22°). With its large uncertainty, this value agrees with the inclination found for the jet to the northeast of the exciting star. That knot A probably has the same inclination as the remainder of the jet is indicated by the presence of the faint high-velocity H\(_2\) component and the high-velocity [Fe \(_{\text{ii}}\)] reported by Fernandes.

### 4.2.3. HH 46F

The object HH 46F lies along the southeastern flank of the ovoid cavity swept out by the counterflow. In the infrared images of Eisloeffel et al. (1994, 2000), the object is seen to be clearly off-axis of the main flow. One is given the impression that the material in HH 46F may represent ambient cloud material that has been entrained in the flare of a bow shock, the apex of which has now propagated toward the southwestern tip of the ovoid cavity about 1.25 times HH 46F. Another possibility is that an inhomogeneous stellar wind in the cavity is producing entrainment of molecular material at the boundary of the cavity. The heliocentric velocity of the material measured from the H\(_2\) emission ranges from about 23 to 31 km s\(^{-1}\) (see Fig. 4). This is slightly greater than the velocity of the ambient cloud material, as would be expected if cloud material has been entrained by the receding outflow.

### 4.3. HH 120

The second H-H system that was discovered in a cometary globule in the Gum Nebula is HH 120 in CG 30 (Reipurth 1981; Pettersson 1984). The distance to this system is estimated to be 450 pc (Graham & Heyer 1989). In optical emission, the object extends about 6" with an east-west orientation and exhibits a protrusion to the north at the western end of the nebula. A strong infrared source (IRS 4) discovered by Pettersson (1984) is generally believed to be the exciting source and is located about 8.5" to the east-southeast of the brighter western knot A in HH 120. The NIR images obtained by Graham & Heyer (1989) and
Gredel (1994) clearly indicate a luminous connection between IRS 4 and the H-H nebula. Pettersson (1984) found that the spectrum of the eastern portion of the nebula (his position B, 5° east of position A) revealed evidence for a red continuum with features typical of a T Tauri star. His infrared aperture photometry identified an infrared source (IRS 3) near that position. The subsequent imaging by Graham & Heyer (1989) and Gredel (1994) suggests that the IRS 3 source may in fact be a reflection nebula. The polarimetry reported by Scarrot et al. (1990) confirms the presence of a reflection nebula, and the geometry suggests that light from IRS 4 is reflected along the walls of a rather narrow cavity that has presumably been formed by the flow responsible for HH 120. The situation appears somewhat analogous to the HH 46 reflection nebula. In addition, Pettersson found that HH 120A revealed a very low excitation optical spectrum similar to that of HH 47A, furthering the analogy with the HH 46/47 system.

Gredel’s infrared H2 image of HH 120 shows a morphology essentially identical to that seen in Figure 5 of this study. Curiously, although Gredel found significant infrared [Fe ii] emission at the location of HH 120A, there is no indication of significant [Fe ii] emission at the position of H2 knot B (Fig. 5). For clarification, we note that the separation of knots A and B in the H2 images is about 2/5, so the spectroscopic position B identified by Pettersson (1984) is actually centered about 2/5 to the east of H2 knot B. Gredel’s infrared [Fe ii] image shows the presence of infrared [Fe ii] knots along the channel between IRS 4 and knot A, a morphology that is not evident in the optical image seen in Pettersson (1984). We interpret this to mean that H-H emission is occurring along the outflow axis, but that the extinction is sufficiently high closer to IRS 4 to obscure the optical components of the emission.

From his optical spectroscopy, Pettersson found a heliocentric radial velocity of −42 ± 12 km s\(^{-1}\) for knot A. From the H2 emission, we find a heliocentric velocity of −39 km s\(^{-1}\) for knot A. In addition, we note evidence in Figure 5 for a secondary condensation at \(v_{\text{helio}} = −5\) km s\(^{-1}\), displaced about 0′′5 toward the flow source. This would be consistent with emission from a clump of material in a bow shock wing extending back from the apex at position A. The close agreement between the atomic and H2 velocities at the apex indicates that, like HH 47A, molecular gas has passed through the bow shock and accelerated to the same velocity as the atomic gas. The very low excitation character of both HH 47A and HH 120A suggests that only partial dissociation of molecules occurs near the apex of the bow shock. It can be noted that the velocity dispersion of the H2 emission in HH 120A is somewhat greater (−30 km s\(^{-1}\)) than found in most of the other H-H knots in this study. This could be the result of excitation at the apex of a bow shock where the velocity dispersion is expected to be a maximum, and the value probably represents the approximate shock velocity of the gas. In the case of HH 120, there are no proper-motion measurements that would permit calculation of the angle of the flow with respect to the plane of the sky. The heliocentric velocity of the cloud is 22.3 km s\(^{-1}\), as determined from CO measurements (Pettersson 1984), so the gas in HH 120A is moving at least 60 km s\(^{-1}\) with respect to the presumed velocity of the exciting star. Pettersson finds little evidence for reddening in HH 120A, so it is possible that the angle of ejection from IRS 4 is greater than 45° with respect to the plane of the sky, given the short projected distance between IRS 4 and HH 120A. With the low-excitation character of the nebula, it is thus possible that the flow is moving into the wake of a previous outflow.

The heliocentric velocity of the dominant component of knot B is about 4 km s\(^{-1}\), again in satisfactory agreement with that found for the optical lines by Pettersson. As noted previously, however, Pettersson’s measurement was made about 2° east of the H2 knot B, and his value of 10 ± 25 km s\(^{-1}\) involved only a few weak lines that were detected at that position. Knot B is immediately adjacent to the axis of the flow from IRS 4 to HH 120A and therefore may represent an ambient molecular clump that has been swept through a bow shock wing extending to the east from HH 120A. The clump has apparently been excited and accelerated to a radial velocity of about 18 km s\(^{-1}\) with respect to the cloud. The lack of a distinct optical emission knot or a NIR [Fe ii] knot at the position of B indicates that the shock velocity is very low, and that few of the molecules are dissociated in the shock. This is what one expects in the extended oblique wing of a bow shock. If this interpretation is correct, it highlights the importance of the inhomogeneous distribution of material (clumps) in the preshock medium, which in fact may have resulted from fragmentation in the passage of earlier shocks. The reflection found by Pettersson in the vicinity of knot B may be related to the higher density material implied by the H2 knot. The deep NIR H2 image of the CG 30 globule obtained by Hodapp & Ladd (1995) shows the presence of additional groups of emission knots that do not align with the IRS 4–HH 120 system. Proper-motion and radial velocity data will be required to determine the probable origin of these structures, which suggest that there may be multiple YSOs in CG 30.

5. SUMMARY

The results of this study indicate that H2 emission in H-H objects kinematically traces that seen in atomic emission. In many cases, H-H objects are propagating into the wakes of previous flows and evidence suggests that the wakes of these flows have resulted in fragmentation and formation of molecular material that becomes the preshock medium for subsequent H-H flows. The deposition of momentum and energy into the ambient medium by an episodic jet is apparently complex with multiple shocks overtaking previously shocked material. Previous studies have shown that, in most cases, jets appear to have sufficient momentum and energy to drive the molecular outflows seen in CO emission (see Chernin & Masson 1995 for models of jet-driven molecular flows). There is evidence that the coupling between the jet and the molecular medium is accomplished both by prompt entrainment in bow shocks (Davis et al. 1997) and by turbulent entrainment along the jet (Micono et al. 2000).

The double velocity peaks seen in HH 38 indicate that the sharp knots probably consist of unresolved bow shocks, with the strongest H2 emission from the lower velocity bow shock wings. In HH 47A, the emission from a region adjacent to the apex of the bow shock is resolved, and the kinematics of the material appear to be fully consistent with that seen in Hα emission, which represents prompt entrainment in the HH 47A bow shock. The HH 46C jet counterflow shows a well-collimated, high-velocity beam (knots B–D), separated from a diffuse base (knot A) that evidently represents a more recent ejection. HH 46C jet A exhibits a strong low-velocity component indicative of excitation of ambient
cloud material in the oblique wings of a bow shock, with a high-velocity component representing the apex of the bow shock. HH 46F can be interpreted either as entrainment of ambient cloud material in the far wings of an extended bow shock outlined by the ovoid cavity, or by entrainment of ambient gas by a stellar wind that flows into the cavity. Finally, HH 120 shows some features that are similar to the HH 47 system, namely, as a flow that has exited the front side of a globule and that is producing very low excitation shocks due to propagation into the wake of a previous outflow. Proper-motion studies of both HH 38 and HH 120 will be required to further illuminate the kinematics of these objects.

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