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# A NEW HERBIG-HARO FLOW IN THE HH 1–2 COMPLEX

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## ABSTRACT

We report the discovery of new faint Herbig-Haro knots in the vicinity of the well-known HH 1-2 bipolar flow. HH 144 forms a well-collimated structure 83″ long with numerous faint knots, while HH 145 is a more disorganized group of knots further to the west. Proper motion measurements of the two brightest knots in HH 144 show a large motion away from the vicinity of VLA 1, the source of the HH 1-2 flow. The alignment of the HH 144 knots suggests, however, that a faint previously known VLA source, VLA 2, located 3″ from VLA 1, is the source of the new flow. This is confirmed by a very deep infrared $K$-band image, which shows reflection nebulae fanning out from VLA 1 toward HH 1 and from VLA 2 toward HH 144. It thus appears that the HH 1-2 source could be a very young binary, with a projected separation of 1380 AU, in which each component drives an independent HH flow. The axes of these two outflows make a large angle to one another.

*Subject headings:* binaries: general — ISM: individual (HH 1-2, HH 144, HH 145) — ISM: jets and outflows — stars: pre–main-sequence

## 1. INTRODUCTION

The first Herbig-Haro (HH) objects discovered were HH 1 and 2, found by Herbig (1951) and Haro (1952). Numerous studies carried out since then have provided a wealth of information about this pair of objects, which are often regarded as the prototypical bipolar HH flow. The proper motion measurements of Herbig & Jones (1981) revealed large transverse velocities, of the order of 300 km s$^{-1}$ for both HH objects. The velocity vectors have opposite directions, pointing away from the now accepted driving source, VLA 1, located on the axis between HH 1 and HH 2 (Pravdo et al. 1985; Rodríguez et al. 1990). The source is not detected by *IRAS*, probably due to confusion (Pravdo & Chester 1987), nor is it seen at near-infrared wavelengths. Instead an elongated infrared reflection nebula appears slightly to the northwest of the source, along the flow axis (Rodríguez, Roth, & Tapia 1985; Tapia et al. 1987; Roth et al. 1989).

Two shock-excited regions are found close to the source. One is a small jet, the HH 1 jet, which starts close to the source and points toward HH 1. The other consists of two small faint knots west of the source (Strom et al. 1985; Bohigas et al. 1985).

## 2. A NEW HIGHLY COLLIMATED HH FLOW

We have obtained a number of interference filter CCD images of the HH 1-2 region at large telescopes (Table 1), which have been added to achieve the hitherto deepest and most detailed view of this star-forming region. In Figure 1*a* (Plate L3) we have identified known and new features, which we discuss in the following.

Just to the west of the location of the VLA source there are two faint HH knots, first noted by Strom et al. (1985) and Bohigas et al. (1985). Their location off the well-defined axis of the HH 1-2 flow has always been puzzling. Our new deep images show that they are only the brighter parts of a long chain of very faint knots stretching toward the west. These knots, which we call HH 144, are labeled in Figure 1b (Plate L3). They are emission-line features, since even the brightest of them is only barely detectable in images taken through a Gunn $z$ filter, which excludes almost all HH emission. The knots lie along a well-defined axis over a total extent of 83″, corresponding to 0.19 pc in projection at the assumed distance of 460 pc. In particular the first three knots, A, B, and the very faint C, appear to delineate a well-collimated HH jet ~20″ long. HH 144A is brighter than B in Hα emission, while the reverse is the case in [S II] emission. Knots D–G lie on the axis of this jet but are more diffuse arcuate features. Finally comes one more compact object, knot H. Further to the west there are additional faint knots, but these are not precisely on the axis of the HH 144 flow, either because the flow bends, or because they belong to a separate flow. We name these additional knots HH 145 and identify them in Figure 1*b* (see Table 2).

The morphology of HH 144 suggests that it emanates from the source region of the HH 1-2 flow. We have compared CCD images taken through [S II] filters during the interval of 4 yr between 1986 November and 1990 November. Even though this interval is relatively short, the proper motion of HH 144A and B is readily detectable. The fanter knots were not detectable in the early images. The Fabry-Perot observations of Noriega-Crespo, Garnavich, & Raga (1993) indicate that HH 144A and B have small radial velocities, ≤50 km s$^{-1}$, indicating that these objects move almost in the plane of the sky. As a check on our procedure we measured the proper motion of HH 1F, and obtained a value in excellent agreement with the earlier determination by Herbig & Jones (1981).

Our proper motions are given in Table 3, and shown in Figure 2. Despite the not negligible uncertainties, it is clear that HH 144A and B move away from the region of the obscured

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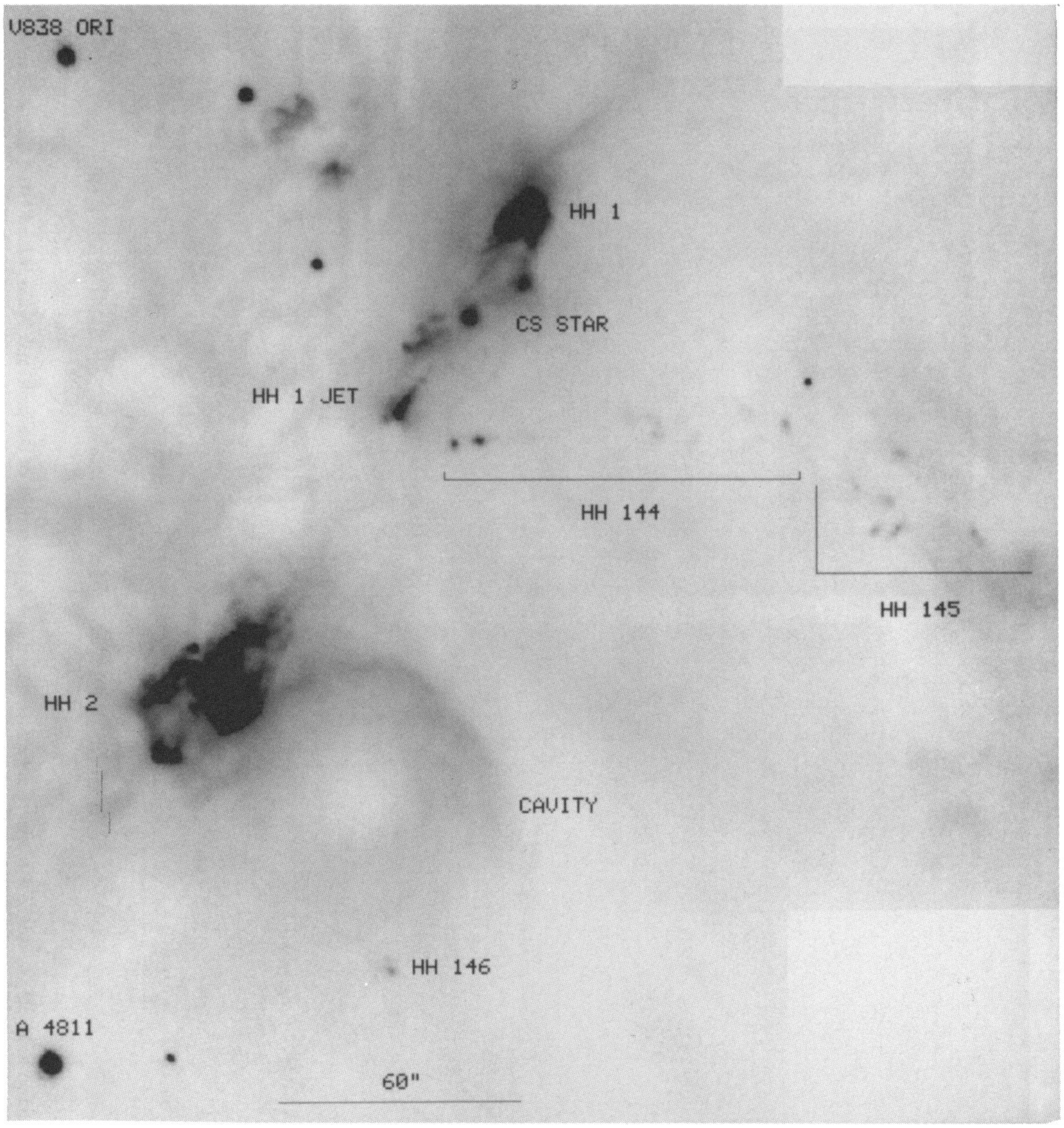


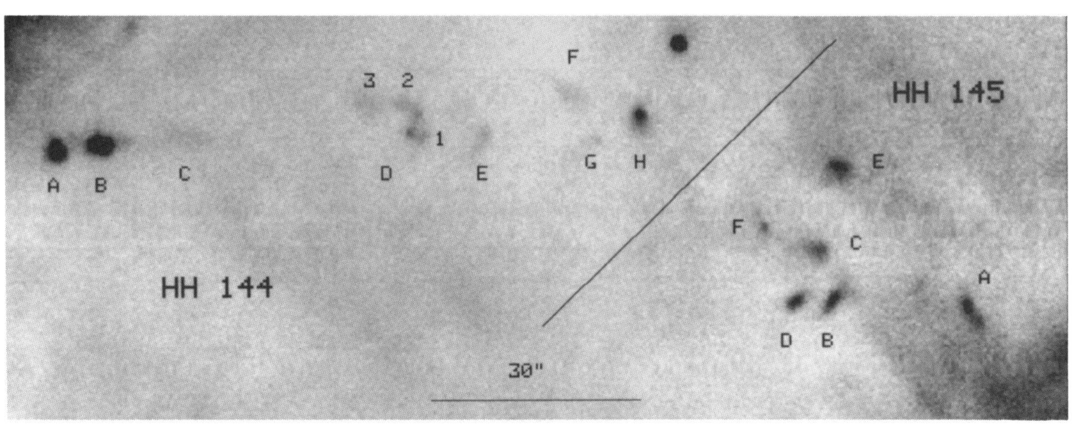


FIG. 1*b*

FIG. 1.—(*a*) A mosaic derived by summing several Hα and [S II] CCD images obtained with the ESO 3.6 m telescope providing an overview of the entire HH 1-2 region. Identifications are given for the various features discussed in the text. North is up and East to the left. (*b*) An enlargement of part of the same image in which the knots comprising HH 144 and 145 are identified. The Hα and [S II] interference filters employed have bandwidths of typically ∼75 Å (FWHM).

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TABLE 1
LOG OF CCD IMAGES

| Date | Filter | Exposure Time (minutes) | Telescope |
|---|---|---|---|
| 1986 Nov 22–23 ....... | [S II] | 5 × 10 | Kitt Peak 2.1 m |
| 1989 Dec 10–11 ....... | [S II] | 20 | ESO NTT[a] |
| 1989 Dec 27–28 ........ | [S II] | 5 × 15 | ESO 3.6 m[b] |
| 1989 Dec 27–28 ........ | Hα | 3 × 10 | ESO 3.6 m[b] |
| 1989 Dec 28–29 ........ | [S II] | 10 | Kitt Peak 2.1 m |
| 1990 Jan 1–2 ........... | [S II] | 3 × 10 | ESO NTT[c] |
| 1990 Nov 21–22 ....... | [S II] | 2 × 5 | ESO NTT[c] |
| 1991 Jan 17–18 ........ | Gunn $z$ | 12 × 4 | ESO NTT[c] |

[a] EFOSC-II.
[b] EFOSC-I.
[c] EMMI.

TABLE 2
POSITIONS OF HH KNOTS AND SOURCES AT EPOCH 1989

| Object | $\alpha_{1950}$ | $\delta_{1950}$ |
|---|---|---|
| HH 144A ......... | 5h33m55s.8 | −6°47′57″ |
| HH 144B ......... | 5 33 55.4 | −6 47 56 |
| HH 144D$_1$ ........ | 5 33 52.4 | −6 47 54 |
| HH 144H ......... | 5 33 50.2 | −6 47 51 |
| HH 145A ......... | 5 33 47.1 | −6 48 19 |
| HH 145B ......... | 5 33 48.4 | −6 48 18 |
| HH 145C ......... | 5 33 48.5 | −6 48 11 |
| HH 145D ......... | 5 33 48.7 | −6 48 18 |
| HH 145E ......... | 5 33 48.3 | −6 47 59 |
| HH 146 ........... | 5 33 56.8 | −6 50 10 |
| VLA 1[a] ............ | 5 33 57.0 | −6 47 55 |
| VLA 2[a] ............ | 5 33 57.1 | −6 47 58 |
| Source 3 .......... | 5 33 57.7 | −6 48 03 |

[a] Positions from Rodríguez et al. 1990 in radio coordinate frame.

VLA source in approximately the direction defined by the HH 144 knots.

If the HH 1-2 source were also responsible for HH 144, an unprecedented wind geometry would be required. We argue in the following that, instead, a second independent source must be driving HH 144. First, the rather well-defined flow axis of HH 144 does *not* pass through the location of the VLA source, but rather several arcseconds south of it. Second, the VLA source was shown by Rodríguez et al. (1990) to be elongated, along a direction toward HH 1 and 2 and not toward HH 144. Third, we note that the very sensitive VLA survey of Rodríguez et al. (1990) revealed a second neighboring faint 6 cm source, which they speculated might be extragalactic, right on the HH 144 flow axis. In the following we refer to this additional source as VLA 2. We have searched for infrared counterparts to these VLA sources in new deep $K$-band images obtained at the 2.5 m duPont telescope of Las Campanas observatory, but neither was detected, probably due to very high extinction. Instead, as shown in Figure 3$a$, our infrared images show the bright reflection nebula, previously discussed by Roth et al. (1989), which is located just to the northwest of VLA 1 and opens out in the direction toward HH 1. In addition our images reveal, for the first time, a faint patch of $K$-band emission just to the south of the main nebula. This feature lies slightly to the west of VLA 2 and is elongated in the direction toward HH 144.

Figure 3$b$ shows a [S II] CCD image including the region in Figure 3$a$. It is evident that just as HH 1, the jet, the infrared reflection nebula, and VLA 1 define a perfect axis, so do the knots in HH 144, the faint southern infrared nebula, and VLA 2. These multiwavelength alignments provide very strong evidence that HH 1-2 and HH 144 are driven by two independent, young stars. It seems highly unlikely that these two outflow sources, located within a few arcseconds of one another on the sky, are unrelated. We believe that they, instead, form a physical binary. The separation between VLA 1 and 2 is 3″.0, which at 460 pc corresponds to 1380 AU in projection, a separation not uncommon among young binaries (Reipurth & Zinnecker 1993).

## 3. STRUCTURE AND PROPER MOTION OF THE HH 1-2 JET

Our images allow a detailed look at the HH 1-2 jet. Figure 3$b$ is from a [S II] image taken in 1989 December at the ESO NTT in 0″.8 seeing. It is here seen that the jet consists of a series of seven individual knots, which we label A–G, forming a highly collimated structure stretching over about 14″, corresponding to 6440 AU, or 0.031 pc, in projection. The HH 1 jet has a number of features in common with other well-collimated HH jets. As it emerges from the molecular material obscuring the driving source, the brightness of the jet increases from knot G to knot F, where it attains a maximum and then gradually fades, with the last knots B and A appearing more diffuse and ill-defined. It shows clear wiggling, particularly pronounced close to the source. It is very much brighter in [S II] than in Hα, except for the first knot G which is stronger in Hα, as also seen in the HH 111 and HH 46-47 jets. The jet is surrounded by a diffuse and somewhat poorly defined reflection nebula; it is not clear if the bright patch (marked "X") 2″ east of knot G belongs to the reflection nebula or is an emission-line feature. It is noteworthy that X appears to emanate from the brightest point in the infrared reflection nebula, whereas the HH 1 jet closely matches the western edge of the reflection nebula. Since the infrared reflection nebula fans out more or less symmetrically from VLA 1, it is tempting to speculate that it might outline a cone carved out because of precession of the jet.

TABLE 3
PROPER MOTIONS OF HH KNOTS

| Object | $\mu_x$ (arcsec/100 yr) | $\mu_y$ (arcsec/100 yr) | $V_x$ (km s$^{-1}$) | $V_y$ (km s$^{-1}$) | P.A. | $V$ (km s$^{-1}$) |
|---|---|---|---|---|---|---|
| HH 144A ......... | −18.4 ± 11.7 | −3.2 ± 5.5 | 401 ± 255 | 70 ± 119 | 260° | 407 ± 272 |
| HH 144B ......... | −12.9 ± 11.8 | −3.5 ± 8.1 | 281 ± 257 | 76 ± 177 | 255 | 291 ± 294 |
| HH 1 Jet .......... | −3.3 ± 7.2 | 10.3 ± 8.5 | 72 ± 157 | 225 ± 185 | 342 | 236 ± 224 |
| HH 1F ............ | −10.0 ± 3.3 | 15.4 ± 4.6 | 218 ± 72 | 336 ± 100 | 327 | 400 ± 123 |

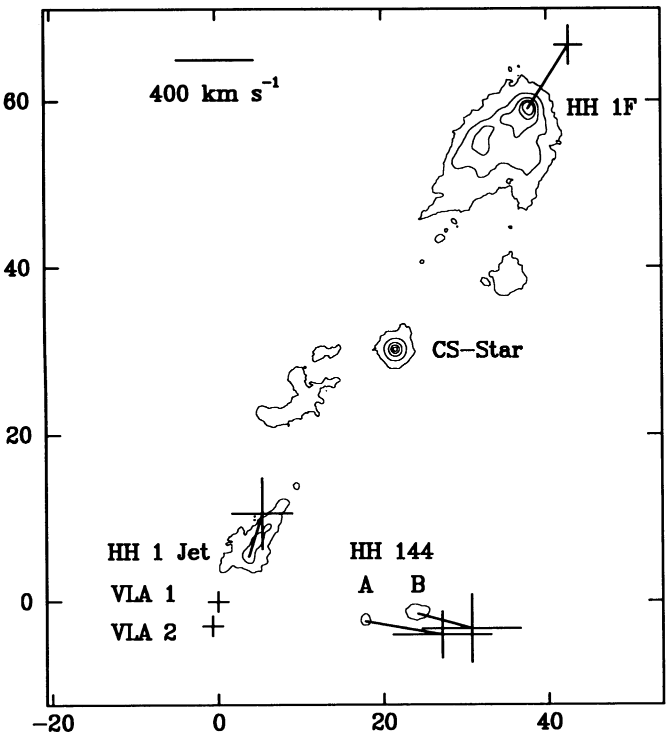


FIG. 2.—Proper motions of Herbig-Haro knots in the HH 1-2 region superposed on a contour plot derived from a [S II] CCD image. Proper motion shifts are indicated for an interval of 50 yr. Error bars show the uncertainty in position after 50 yr due to the error in the proper motion determination.

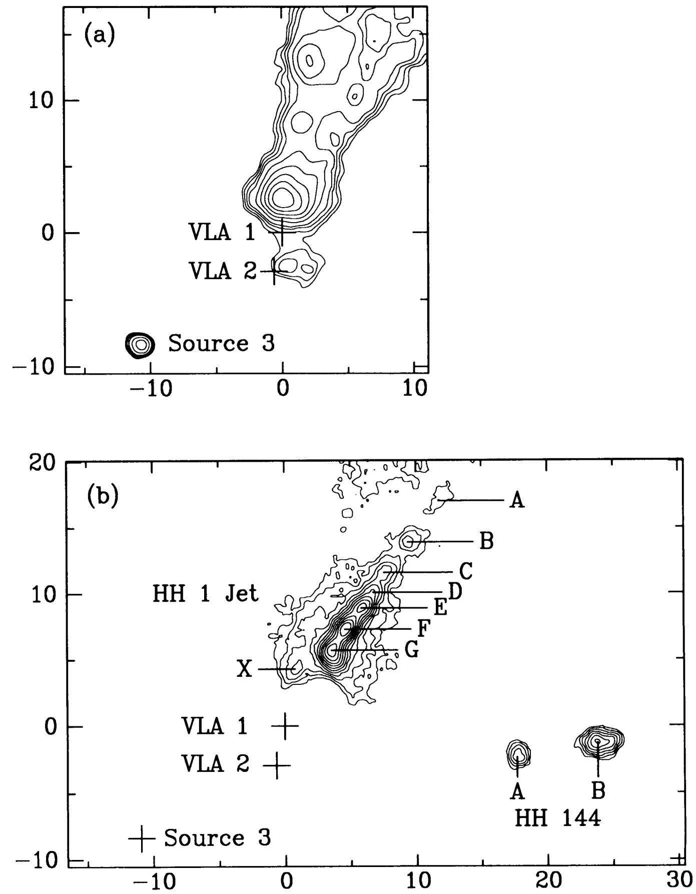


FIG. 3.—(*a*) Contour diagram derived from a deep *K* image of the source region in the HH 1-2 region. The positions of the two VLA sources (invisible at *K*) are marked. The well-known discrepancy between optical and radio coordinate systems in this region (Rodríguez et al. 1990), in the sense that optical positions are shifted about 1″ to the northwest, has been compensated for when placing the sources in the figure. Coordinates are in arcseconds with VLA at the origin. A Rockwell 128 × 128 pixel Hg-Cd-Te device giving a scale of 0″.52 pixel$^{-1}$ was used (Persson et al. 1992). The total integration time was 2040 s, divided between 17 groups of six 20 s integrations, with small telescope shifts between each group. (*b*) A high-resolution [S II] CCD image obtained at the ESO NTT including the source region and the HH 1 jet. The scale and orientation is the same as for the infrared image. The uncertainty of the source positions corresponds to the size of the crosses.

From its similarity to other HH jets and its precise location along the HH 1-2 flow axis, which is close to the plane of the sky, we expect the HH 1 jet to show substantial proper motion. Despite the relatively short time interval of our CCD images we indeed detect a proper motion (see Table 3 and Fig. 2). The tangential velocity is around 200 km s$^{-1}$ and is, as expected, directed along the flow axis, although the uncertainty in the determination is quite large.

## 4. CLOUD STRUCTURE

In Figure 4*a* (Plate L4) we show the sum of the Hα and [S II] images obtained with the ESO 3.6 m telescope, presented in such a way that all the faintest features in the region stand out. The figure gives the first detailed view of the surface of the molecular cloud behind HH 1 and 2. The cloud appears to have a well-defined interface to the ambient medium, showing up as a fairly luminous skin of Hα emission, presumably excited by the interstellar UV radiation field, which may be enhanced in this neighborhood of young massive stars. A region of high extinction appears to stretch across the embedded sources, perpendicular to the flow, and corresponding approximately to the dense $NH_3$ ridge observed by Marcaide et al. (1988).

Figure 4*b* (Plate L4) shows a deep Gunn *z* image of the HH 1-2 region. Whereas the Hα plus [S II] image in Figure 4*a* emphasizes emission-line features, Figure 4*b* outlines regions in either direct or reflected continuum light. One clearly sees the shaft of light illuminating the flow channel between VLA 1 and HH 1, already commented upon by Strom et al. (1985), and here seen in much greater detail. But we also see a similar, albeit fainter, channel which opens toward the southeast in the flow direction of HH 2. We particularly note that knot L in HH 2, the knot furthest away from the source, is embedded in a large curved reflection structure, as if the flow is here encountering an obstacle illuminated, through the flow channel, by the embedded source. It is interesting that this reflection nebula appears to coincide with a small dense clump detected in $HCO^+$ and $NH_3$ (Davis, Dent, & Burnell 1990; Torrelles et al. 1992). Two more patches of reflected light are seen even further downstream.

All images of HH 1-2 starting with the earliest photographs have shown the presence of a large curious half-moon shaped feature just west of HH 2 (see Fig. 4*a*). The east-west diameter of the half-circle is 50″, corresponding to 0.11 pc. Comparison of Hα and [S II] images shows that the luminous rim is mostly Hα emission. We have also found a small faint HH object, here called HH 146, slightly south of the center of this luminous rim.

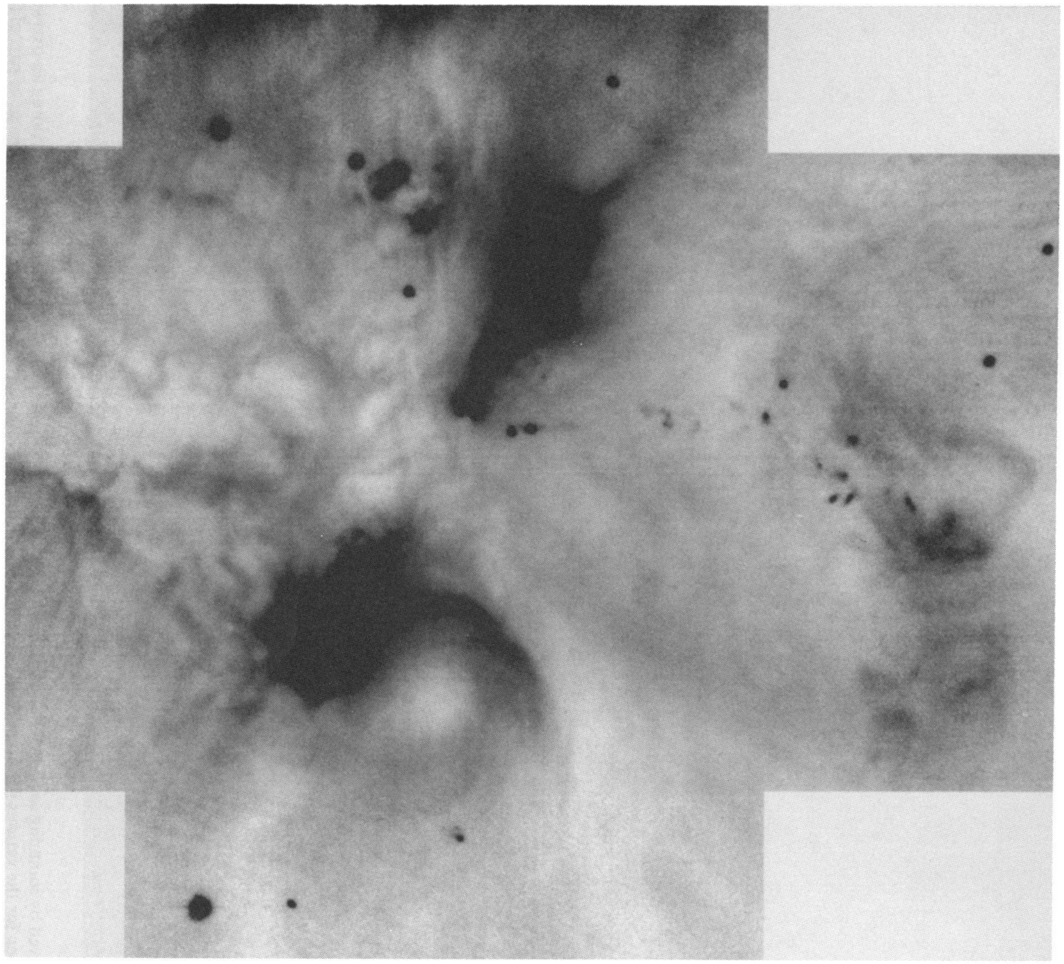

Fig. 4a

Fig. 4b

Fig. 4.—(*a*) The Hα plus [S II] CCD image of Fig. 1 presented so as to emphasize the extremely faint emission features of the surface of the molecular cloud behind HH 1 and 2. Several anonymous HH objects not discussed in this *Letter* can also be seen. (*b*) A deep 1 μm CCD image taken through a Gunn *z* filter, which mainly transmits continuum light and a few HH emission lines. A major reflection nebula, due to the HH 1-2 source, illuminates the cavity through which HH 1 has passed.

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We speculate that the rim could be a cavity blown by a stellar wind, which breaks through the surface of the molecular cloud and originates from a young star embedded near VLA 1 and 2. Our deep *K*-image reveals the presence of a faint (*K* about 16.2) and very red source, here labeled source 3, located near VLA 1 and 2.

## 5. DISCUSSION

In this *Letter* we have suggested that the HH 1 and 2 energy source could be one component of a young embedded binary with a projected separation of 1380 AU. If so, this would not be the first binary found among HH energy sources; at least seven others are known: T Tau, L1642−2, Z CMa, Sz 68, SR 24, S CrA, and AS 353. However, evidence that the two component stars drive separate outflows has been found in none of these cases. Several jets emanate from the trapezium-type clusterings around HL Tau and around SVS 63, but the dynamical relation between these components is unclear (Mundt, Ray, & Bührke 1988; Mundt, Ray, & Raga 1991). The case of VLA 1 and 2 may allow a first insight into the distribution of circumstellar material around a PMS binary. In the following discussion we assume that the two stars are physically related.

VLA 1 and 2 are surrounded by a large extended envelope of cold dust; the 1300 $\mu$m observations of Reipurth et al. (1993) suggest a total circumbinary mass of about 1–4 $M_\odot$. With their relatively large separations, the individual stellar components are likely to be surrounded by separate circumstellar disks. It is unclear, on theoretical grounds, whether such individual disks should be coplanar. However, if the HH flow from each source emerges perpendicular to the surrounding disk, then this, apparently, is not the case. Nor is it clear whether the orbital vector of a binary should be parallel to the principal outflow axis. If this is the case, then VLA 1 and VLA 2 lie in an orbit almost perpendicular to the plane of the sky, and thus, from their observed geometry, their real separation would be considerably larger than their projected separation.

There is some indirect evidence that the primary component of the system is the one driving the HH 1-2 flow. First, the HH 1-2 flow is much brighter, and thus presumably more powerful than HH 144. Second, VLA 1 is much brighter at 6 cm than VLA 2 (Rodríguez et al. 1990). Third, the axis of the HH 1-2 flow is well aligned with all the other HH flows in its immediate surroundings (Reipurth 1989), while HH 144 deviates completely from this common flow direction. Altogether, this could perhaps imply that the main mass is associated with VLA 1 and that it perturbs the smaller mass around VLA 2, setting up a strong precession of the latter's disk.

The projected separation of 1380 AU between VLA 1 and VLA 2 puts a lower limit of 15,000 yr to the orbital period of the system, if one assumes a total binary stellar mass of 1.5 $M_\odot$. If to this one adds another approximately 1 $M_\odot$ of circumstellar material partaking in the orbital motion, this limit becomes 11,500 yr. HH 144H is 104″ from VLA 2; assuming a tangential velocity of 350 km $s^{-1}$, the dynamical age of HH 144 becomes of the order of 650 yr, much shorter than the orbital period. It is then not surprising that orbital motion has had little effect on the appearance of the jet. If the direction of the jet is related to the orientation of the disk around VLA 2, it similarly follows from the near-perfect collimation of HH 144 that the precession period of the disk must be significantly larger than the jet dynamical age of 650 yr. At present it is not possible to determine if the location of HH 145 off the well-defined axis of HH 144 is due to a previous gradual change in the axis of ejection, or if HH 145 results from a further independent flow; proper motion measurements some years from now may help resolve this.

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## REFERENCES

Bohigas, J., et al. 1985, Rev. Mexicana Astron. Af., 11, 149
Davis, C. J., Dent, W. R. F., & Burnell, S. J. B. 1990, MNRAS, 244, 173
Haro, G. 1952, ApJ, 115, 572
Herbig, G. H. 1951, ApJ, 113, 697
Herbig, G. H., & Jones, B. F. 1981, AJ, 86, 1232
Marcaide, J. M., Torrelles, J. M., Gusten, R., Menten, K. M., Ho, P. T. P., Moran, J. M., & Rodríguez, L. F. 1988, A&A, 197, 235
Mundt, R., Ray, T. P., & Bührke, T. 1988, ApJ, 333, L69
Mundt, R., Ray, T. P., & Raga, A. C. 1991, A&A, 252, 740
Noriega-Crespo, A., Garnavich, P., & Raga, A. C. 1993, in preparation
Persson, S. E., West, S. C., Carr, D. M., Sivaramakrishnan, A., & Murphy, D. C. 1992, PASP, 104, 204
Pravdo, S. H., & Chester, T. J. 1987, ApJ, 314, 308
Pravdo, S. H., Rodríguez, L. F., Curiel, S., Cantó, J., Torrelles, J. M., Becker, R. H., & Sellgren, K. 1985, ApJ, 293, L35
Reipurth, B. 1989, A&A, 220, 249
Reipurth, B., Chini, R., Krügel, E., Kreysa, E., & Sievers, A. 1993, A&A, in press
Reipurth, B., & Zinnecker, H. 1993, A&A, in press
Rodríguez, L. F., Ho, P. T. P., Torrelles, J. M., Curiel, S., & Cantó, J. 1990, ApJ, 352, 645
Rodríguez, L. F., Roth, M., & Tapia, M. 1985, MNRAS, 214, 9P
Roth, M., Tapia, M., Rubio, M., & Rodríguez, L. F. 1989, A&A, 222, 211
Strom, S. E., Strom, K. M., Grasdalen, G. L., Sellgren, K., Wolff, S., Morgan, J., Stocke, J., & Mundt, R. 1985, AJ, 90, 2281
Tapia, M., Roth, M., Carrasco, L., & Ruiz, M. T. 1987, MNRAS, 224, 587
Torrelles, J. M., Rodríguez, L. F., Cantó, J., Anglada, G., Gómez, J. F., Curiel, S., & Ho, P. T. P. 1992, ApJ, 396, L95