

SHOCKED MOLECULAR HYDROGEN AND JETS IN STAR-FORMING CLOUDS. II.

ADAIR P. LANE

National Radio Astronomy Observatory,¹ Charlottesville, Virginia, and Astronomy Department, Boston University

AND

JOHN BALLY

AT & T Bell Laboratories, Holmdel, New Jersey

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ABSTRACT

Extensive mapping of the $2\ \mu\text{m}$ $v=1-0$ $S(1)$ line of molecular hydrogen in the star-forming regions NGC 2071 and NGC 1333 (HH 12) is presented. In NGC 2071, the H_2 emission indicates the presence of a pair of oppositely directed supersonic jets emerging from the newly formed cluster of stars at the center of the molecular cloud. The overall extent of the molecular hydrogen emission is comparable to the extent of the high-velocity molecular gas traced by the low-lying millimeter-wavelength emission lines of carbon monoxide. The infrared observations, however, show the flow to be more collimated than is indicated by the CO data, probably because of the higher resolution of the infrared data. As is the case in the Orion star-forming region, the strongest H_2 emission occurs at the outer periphery of the high-velocity flow. The H_2 emission associated with the redshifted portion of the NGC 2071 flow exhibits a prominent $1'$ wide gap between it and the central infrared cluster. This feature may be explained as an extinction feature of a tilted sheet or disk of gas centered on the infrared cluster. The northeastern (blueshifted) portion of the flow presumably lies in front of the sheet and does not suffer extinction; the southwestern (redshifted) flow, however, may suffer about 3 mag of extinction at $2\ \mu\text{m}$, if most of the dense carbon monosulfide (CS) emitting gas seen in this direction lies in front of the H_2 emitting gas. We detected a total of four lines of the H_2 vibration-rotation quadrupole bands from NGC 2071. The vibrational temperature of the H_2 gas is derived to be 2690 ± 220 K. The total luminosity radiated by the H_2 molecule, corrected for extinction, is $\sim 11 L_\odot$. This probably represents the energy radiated by cooling gas lying behind shock waves generated by a high-velocity wind from the central infrared cluster where it encounters dense gas.

In HH 12 the H_2 emission shows a high degree of correlation with the distribution of the bright optical emission, indicating close connection between excitation of near-infrared H_2 emission and visible line emission of Herbig-Haro objects. However, we find no detectable H_2 emission along the narrow, sinuous jet observed in $\text{H}\alpha$ directly south of HH 12. We also report detection of H_2 emission from HH 6 and from the high-velocity flow associated with Mon R2. We present upper limits for the $S(1)$ line for several other Galactic and extragalactic sources.

A new method for computing the mass-loss rate and wind velocity of the driving engine responsible for collimated outflows is demonstrated. Using the observed luminosity radiated by gas where the collimated flow deposits its bulk kinetic energy and pressure, it is possible to derive the mass flow rate and flow velocity in the jet. This method gives a mass-loss rate for the NGC 2071 source of $\dot{M}_* = 3.7 \times 10^{-5} M_\odot \text{yr}^{-1}$ at a velocity $V_j = 115 \text{ km s}^{-1}$; for HH 12 we derive $\dot{M}_* = 4.6 \times 10^{-7} M_\odot \text{yr}^{-1}$ at $V_j = 228 \text{ km s}^{-1}$.

Subject headings: interstellar: molecules — nebulae: individual — shock waves — stars: formation

1. INTRODUCTION

Near-infrared emission lines from vibrationally excited molecular hydrogen provide a powerful probe of the energetic activity inside molecular clouds. Since the initial discovery of the $2\ \mu\text{m}$ quadrupole emission lines from the $v=1-0$ vibration-rotation transitions observed in the Orion Nebula (Gautier *et al.* 1976), a large variety of astronomical sources have been observed in these transitions. These H_2 lines have been seen in planetary and protoplanetary nebulae (Treffers *et al.* 1976; Beckwith, Persson, and Gatley 1978; Thronson 1981), external galaxies (Thompson, Lebofsky, and Rieke 1978; Fischer *et al.* 1983), supernova remnants (Treffers 1979), and many star-forming regions (Fischer, Righini-Cohen, and Simon 1980; Fischer *et al.* 1980; Elias 1980; Bally and Lane

1982; Fischer *et al.* 1982; Simon and Joyce 1983; see Shull and Beckwith 1982 for a review). The molecular hydrogen emission in star-forming regions is closely associated with other indicators of high-velocity, highly supersonic outflows of gas, as indicated by proper motions of water masers and Herbig-Haro objects and by broad molecular emission lines. In these sources, the molecular hydrogen emission is collisionally excited in dense gas which has passed through an energetic ($v > 10 \text{ km s}^{-1}$) shock wave. The near-infrared transitions of H_2 trace the location of shock waves associated with supersonic gas flow in star-forming regions.

Recent observations have shown that energetic activity in star-forming clouds consists of the supersonic ejection of gas from the vicinity of newly formed stars into two collimated, oppositely directed jets. In regions of massive star formation, the jets are seen as high-velocity bipolar outflows in the millimeter-wavelength transitions of molecules such as carbon

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monoxide (Rodríguez, Ho, and Moran 1980; Lada and Harvey 1981; Bally 1982; Rodríguez *et al.* 1982; Bally and Lada 1983). Regions of low-mass star formation which contain Herbig-Haro objects also exhibit bipolar molecular emission (Snell, Loren, and Plambeck 1980; Snell and Edwards 1981, 1982; Edwards and Snell 1983). Very deep optical imagery of regions of low-mass star formation has dramatically demonstrated the high degree of collimation of the high-velocity gas. In HH 46–47, an optical jet over 1' in length and only several arcseconds in width, moving with a line-of-sight velocity greater than 150 km s⁻¹, has been observed (Graham and Elias 1983). Optical jets have also been observed in association with the Herbig-Haro objects HH 32 A–C (Mundt, Stocke, and Stockman 1983); HH 7–11 and HH 12 (Strom, Strom, and Stocke 1983); HL Tau, DG Tau, DG Tau B, HH 30, and L1551 IRS 5 (Mundt and Fried 1983); and several other sources (Mundt *et al.* 1984; Brugel, Mundt, and Bührke 1984). Large proper motions indicating ejection into two narrow oppositely directed cones have been measured for HH 1–2 by Herbig and Jones (1981), suggesting highly collimated ejection. Although many regions containing bipolar molecular outflows, Herbig-Haro objects, and optical jets have been detected in the 2 μ m transitions of H₂, only the flow associated with the BN–KL infrared cluster behind the Orion Nebula has been mapped extensively (Beckwith *et al.* 1978; Nadeau, Geballe, and Neugebauer 1982; Scoville *et al.* 1982). Although it is now known that molecular clouds exhibiting energetic activity radiate in the 2 μ m H₂ lines, virtually nothing is known about the morphology and distribution in the plane of the sky of the 2 μ m emission regions.

In this paper we present extensive mapping of the 2.12 μ m $v = 1-0$ S(1) line of molecular hydrogen in the sources NGC 2071 located in the Orion molecular cloud and HH 12 located in the NGC 1333 cloud in Perseus. The first source is a region of massive star formation spawning B3 or B4 stars, while the second region is producing only low-luminosity stars. Mapping of the H₂ S(1) line in these sources provides an opportunity to probe the structure of the shock fronts associated with energetic high-velocity gas with an angular resolution around 15". The millimeter-wavelength studies of the high-velocity outflow phenomena are limited by the angular resolution of currently available telescopes to 30" or worse. Since optical studies are hampered by the extinction of the associated molecular cloud (often $A_v > 30$ mag), near-infrared observations provide the best opportunity to study energetic activity in molecular clouds with arcsecond resolution.

II. OBSERVATIONS

The observations reported here were made with the 2.1 and 1.3 m telescopes located on Kitt Peak² between 1983 January 20 and January 31. The 2.1 m telescope was used with the liquid nitrogen-cooled InSb infrared detector mounted in the Dewar known as "Blue Toad." The cold station contains a circular variable filter (CVF) with a spectral resolution of 1.3% in the 2 μ m window. The Dewar also is equipped with standard J , H , K , L , and M broad-band photometric filters for operation between 1 and 4 μ m wavelength.

Observations of the 2.12 μ m H₂ $v = 1-0$ S(1) line were made

with the CVF by observing at the S(1) line wavelength and at two adjacent wavelengths 0.04 μ m above and below to remove continuum emission from the beam. Both the narrow- and broad-band observations used a chopping secondary mirror, vibrating at 5 Hz, to subtract atmospheric and instrumental emission. Beam throws between 60" and 200" were used; the actual throw was chosen to eliminate unwanted stars from the reference beam. The Dewar known as "Hermann," also equipped with an InSb detector and a CVF, was used on the 1.3 m telescope to make measurements of the $v = 1-0$ S(0), S(1), and S(2) lines and the $v = 2-1$ S(1) line in NGC 2071. Intensity calibration was accomplished in all cases by observations of the star 39 Cnc, which has a K magnitude of 4.23 ($S_{2.2 \mu m} = 12.6$ Jy).

III. RESULTS

a) NGC 2071

i) Previous Observations

Four arcminutes north of the reflection nebula NGC 2071 lies an active star-forming region usually referred to by the same name. This complex is located inside the northern part of the Orion B molecular cloud at a distance of 500 pc. The total infrared luminosity of the star-forming region has been measured to be in the range $L = 750-1000 L_\odot$ (Harvey *et al.* 1979; Sargent *et al.* 1981), indicating one or more zero-age main-sequence (ZAMS) stars with spectral type in the range B3–B5. The infrared source at 10 μ m contains at least three components separated by about 8" (Persson *et al.* 1981). OH and H₂O maser emission is also observed close to the infrared cluster (Pankonin, Winnberg, and Booth 1977; Campbell 1978). Radio continuum observations made at centimeter wavelengths with the VLA show three compact H II regions associated with the three 10 μ m infrared peaks (Bally and Predmore 1983; Snell and Bally 1986), and a fourth component near the outer tip of the northeast lobe of molecular hydrogen emission (see Fig. 4).

The NGC 2071 infrared cluster is positioned near the center of an energetic bipolar molecular outflow having a full width in the 115 GHz transition of ¹²CO of 70 km s⁻¹, the second highest velocity outflow known (Bally 1982). The high-velocity flow exhibits blueshifted emission in the northeast and redshifted emission to the southeast of the infrared cluster. The high-velocity flow region is about 5' long, corresponding to 0.75 pc at an assumed distance of 500 pc. The width of the flow observed in $J = 2-1$ CO is 1'–2'. The high-velocity CO emission is best modeled as originating from numerous dense clumps of gas swept up into a thin shell which is plowing into the ambient molecular cloud, driven by the force of a collimated stellar wind (Snell *et al.* 1984).

High-velocity atomic hydrogen emission at 21 cm exhibits a line width of $\Delta v = 120$ km s⁻¹ in the vicinity of the NGC 2071 infrared cluster (Bally and Stark 1983). Shock-excited infrared molecular hydrogen emission in the $v = 1-0$ S(1) line at 2.12 μ m was detected at several locations in the high-velocity flow region by Bally and Lane (1982 [Paper I]) and, independently, by Simon and Joyce (1983). At the position of IRS 2, Persson *et al.* (1981) found the width of the S(1) line to be 100 km s⁻¹ with a prominent blueshifted wing. The detection of both high-velocity H I and high-velocity H₂ makes NGC 2071 an ideal testing ground for models of the shock structure associated with high-velocity molecular gas (Chernoff, Hollenbach, and McKee 1982; Draine and Roberge 1982).

² Kitt Peak National Observatory is operated by Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

ii) *Spatial Distribution of the H₂ Emission*

The new observations reported here cover about 100 map points (300 if the reference positions observed by the chopping secondary mirror are considered) in the NGC 2071 region. Figure 1 shows a contour map of the distribution of H₂

$v = 1-0$ S(1) line emission in NGC 2071, along with the locations of H₂O and OH masers and the infrared cluster. The coverage and aperture sizes used to construct the map are shown to the same scale in Figure 2. The extent of the emission region to the southeast has been somewhat less well con-

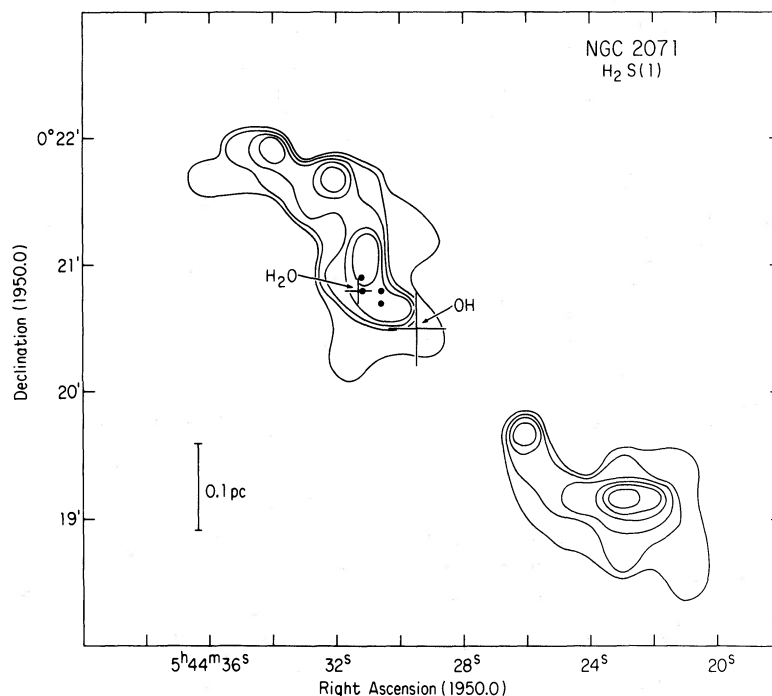


Fig. 1.—The NGC 2071 molecular hydrogen emission in the $v = 1-0$ S(1) transition. Beam sizes and the spatial sampling used to produce the map are shown in Fig. 2. Contour levels are $8.9, 7.1, 5.3, 3.6, 1.8,$ and $0.6 \times 10^{-5} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$. Filled circles mark the positions of the $10 \mu\text{m}$ infrared sources detected by Persson *et al.* (1981).

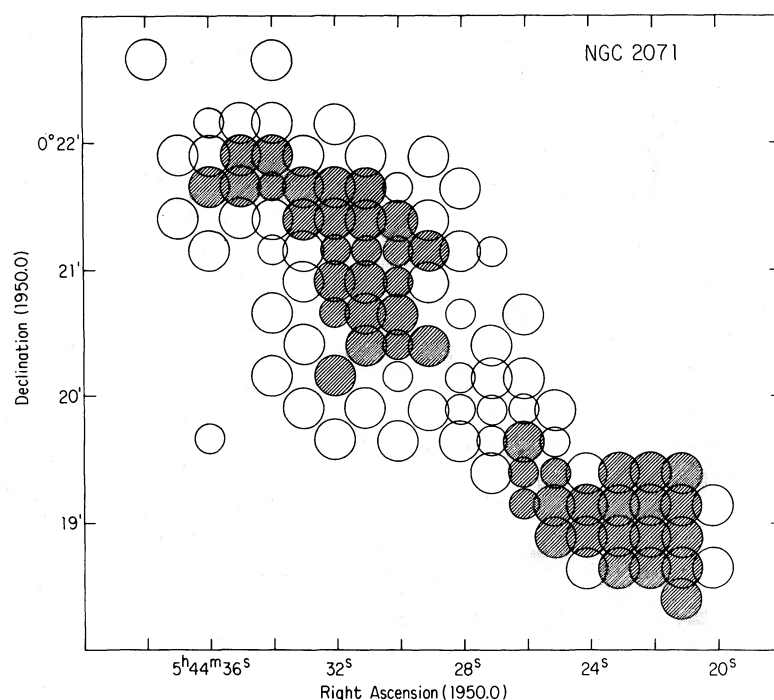


Fig. 2.—Aperture sizes ($15''$ and $21''$) and spatial sampling of the $v = 1-0$ S(1) line observations used to construct the map in Fig. 1. Hatched circles indicate positions where emission was detected; open circles indicate nondetections.

strained by the observations than has the northwest emission lobe. Figure 3 shows for comparison a contour map of the distribution of high-velocity $J = 2-1$ CO emission observed by Snell *et al.* (1984). These data show a $15''$ offset of the major axis of the CO emission region from the infrared cluster. The H₂ data (Fig. 1) do not show a comparable offset, but instead are centered on the infrared cluster. Figure 4 shows the 5 GHz radio continuum map obtained with the VLA by Snell and Bally (1986).

A number of features of the H₂ emission are apparent from the S(1) line map: (1) The H₂ S(1) line is formed in an elongated structure having roughly the same extent and orientation as the high-velocity CO emission. The emission region is roughly $5'$ long (0.75 pc) and less than $1'$ wide. (2) Five distinct peaks of H₂ emission are identifiable on the map. It is likely that several of these peaks are unresolved by our observations. The five peaks are not collinear on the plane of the sky, but curve slightly into an extended S-like distribution. (3) The strongest H₂ emission occurs 2.5 southwest of the infrared cluster, near the southern *outer* edge of the redshifted molecular gas detected by the CO observations. This emission peak is also at the outer edge of the redshifted high-velocity emission detected in HCO⁺ by Wootten *et al.* (1984). This situation is similar to that in Orion where the shocked molecular hydrogen also appears to peak near the boundaries of the high-velocity molecular emission region (Erickson *et al.* 1982). However, the high-velocity CO region in NGC 2071 (as measured by Snell *et al.* 1984) extends somewhat farther to the north than does the H₂ line emission region. (4) Although the strongest peak occurs in the southwest emission lobe, 60% of the total flux comes from the northeast emission lobe associated with the *blue-shifted* CO emitting gas. (5) The positions of the H₂ emission peaks do not correspond in detail with positions of IR sources, masers, 6 cm continuum emission, or peaks of high-velocity

molecular emission. We estimate our pointing accuracy to be $\sim 5''$. (6) There is a $1'$ gap in the S(1) line emission map immediately to the southwest of the infrared cluster. This feature is discussed further in § IV. (7) The overall degree of collimation exhibited by the H₂ S(1) line is somewhat greater than that of the CO emission as observed with a $23''$ telescope beam. The $15''$ – $20''$ resolution of the infrared observations is still insufficient to resolve the smallest scale structure in the source.

These observations result in the best resolved map of a bipolar molecular outflow observed to date. The close association of the distribution of the H₂ S(1) line emission with the CO emission suggests that we are observing the shock waves associated with a highly collimated pair of supersonic jets emerging from the vicinity of the infrared cluster.

iii) Physical Parameters of the H₂ Gas

The intensities of the $v = 1-0$ S(1) line at the five emission peaks in NGC 2071 are listed in Table 1 with their respective positions. These peak intensities are 2 orders of magnitude weaker than the peak intensities observed in the Orion BN-KL source (cf. Beckwith *et al.* 1978; Scoville *et al.* 1982). The NGC 2071 H₂ emission region is, however, 3–4 times larger in spatial extent than is the Orion source. The total $v = 1-0$ S(1) line flux detected from the entire NGC 2071 flow is 1.17×10^{-18} W cm⁻², which corresponds to an S(1) line luminosity of $0.09 L_{\odot}$ if no correction is made for extinction.

The intensities of the $v = 1-0$ S(0), S(1), and S(2) and $v = 2-1$ S(1) lines measured at the position $\alpha_{1950} = 5^h44^m32^s.1$, $\delta_{1950} = 0^{\circ}21'40''$ are also presented in Table 1 and have been used to derive column densities of H₂ in the vibrationally excited levels, assuming the lines are optically thin, using

$$N(v, J) = \left(\frac{4\pi}{h\nu A} \right) I.$$

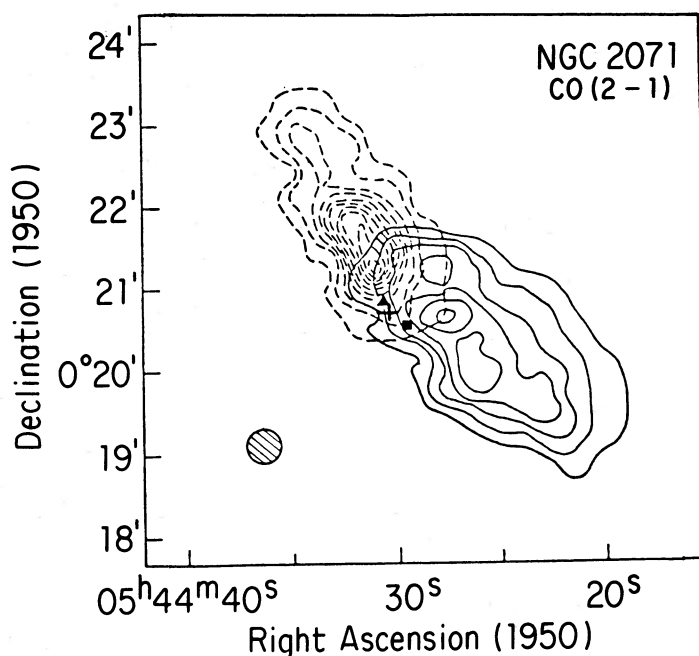


FIG. 3.—Distribution of high-velocity $J = 2-1$ CO emission toward NGC 2071 observed by Snell *et al.* (1984) with the FCRAO 13.7 m telescope. Dashed contours indicate blueshifted (-20 to $+5$ km s⁻¹) high-velocity emission, and solid contours indicate redshifted (15 – 30 km s⁻¹) high-velocity emission. The plus sign indicates the location of the $10 \mu\text{m}$ and VLA sources, the filled triangle the location of the H₂O maser, and the filled square the location of the OH maser. The HPBW is shown by the hatched circle.

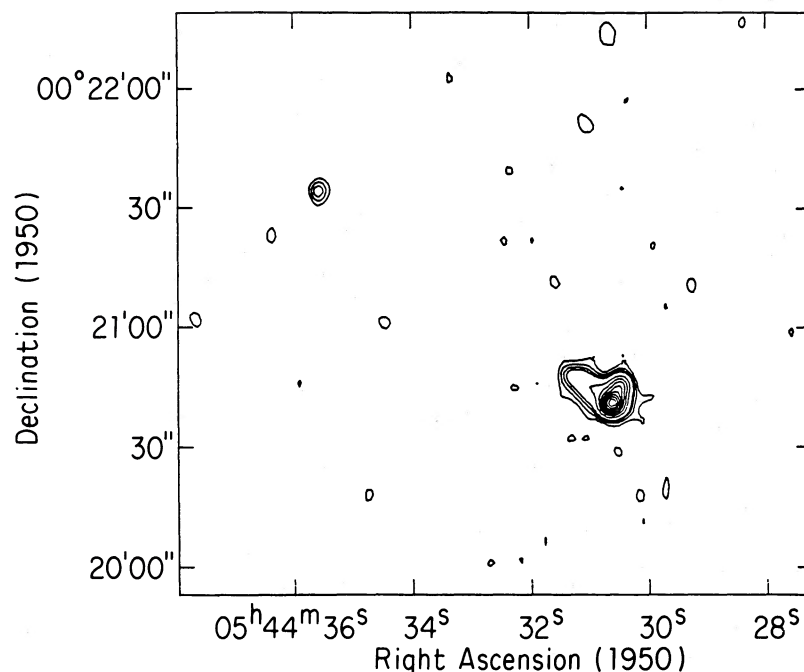


FIG. 4.—A 5 GHz radio continuum map obtained with the 3 km (C) array of the VLA showing the radio emission associated with the NGC 2071 infrared cluster (Snell and Bally 1986). The component in the upper left-hand portion of the map lies near the outer tip of the northeast lobe of H_2 emission.

Einstein A coefficients from Turner, Kirby-Docken, and Dalgarno (1977) have been used, with transition rest frequencies from Scoville *et al.* (1982), derived from molecular constants in Fink, Wiggins, and Rank (1965). Figure 5 shows a plot of the normalized column densities of molecules in the state (v, J) versus the energy of the state above the ground state. If the level populations are in a Boltzmann distribution and the molecules are excited by collisions, the slope of a line through the plotted points is inversely proportional to the excitation temperature. From the line drawn through the $v = 1-0$ and the $v = 2-1$ $S(1)$ points, a vibrational excitation temperature of 2690 ± 220 K is derived. The rotational temperature obtained from the $v = 1-0$ $S(0)$, $S(1)$, and $S(2)$ measurements is 1420 ± 240 K. For a vibrational temperature of 2690 K we calculate the total column density of hot H_2 (all levels) to be $1.19 \times 10^{17} \text{ cm}^{-2}$. The total mass of emitting molecular hydrogen is $\sim 1 \times 10^{-4} M_\odot$, and the H_2 luminosity (all lines) is $\sim 1 L_\odot$. Since we have neglected the effects of extinction at $2.1 \mu\text{m}$, these estimates are lower limits. The total H_2 luminosity corrected for 2.7 mag of extinction at $2.1 \mu\text{m}$ (see discussion in § IV) is $\sim 10.8 L_\odot$.

b) HH 12 and HH 6 (NGC 1333 Region)

i) Optical, Radio, and Broad-Band Infrared Data

Several arcminutes south of the reflection nebula NGC 1333 lies a cluster of Herbig-Haro objects described by Herbig (1974), Strom, Grasdalen, and Strom (1974), and more recently by Cohen and Schwartz (1983). The most prominent objects are the chain HH 7 to HH 11, HH 12, and HH 6. The HH objects lie close to the core of a large molecular cloud (Loren 1976) which has densities sufficient to excite the 2 mm transitions of H_2CO (Lada *et al.* 1974). A bipolar molecular outflow was found in the vicinity of HH 7–11 by Snell and Edwards (1982). The blueshifted part of this flow is roughly centered on HH 7–11, while the redshifted part lies to the northwest, where no nebulosity is seen.

More recently, Edwards and Snell (1983) found evidence for another high-velocity outflow near HH 12. The optical emission knots of HH 12 are coincident with high-velocity ($\Delta v_{\text{max}} = 20 \text{ km s}^{-1}$) blueshifted gas; the knots themselves have radial velocities of -65 km s^{-1} relative to the molecular cloud (Strom, Grasdalen, and Strom 1974). Corresponding redshifted

TABLE 1
INTENSITIES OF H_2 LINES IN NGC 2071

PEAK POSITION		INTENSITIES ($\times 10^{-5} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$)				COLUMN DENSITY ^a $N(H_2)$ ($\times 10^{17} \text{ cm}^{-2}$)
		$v = 1-0$ $S(0)$	$v = 1-0$ $S(1)$	$v = 1-0$ $S(2)$	$v = 2-1$ $S(1)$	
α_{1950}	δ_{1950}					
05 ^h 44 ^m 34 ^s .1	0°21'55"	...	6.16	...	...	...
05 44 32.1	0 21 40	1.78	7.14	2.50	1.21	1.19
05 44 31.1	0 21 05	...	7.58	...	...	...
05 44 26.1	0 19 40	...	5.56	...	...	...
05 44 23.1	0 19 10	...	9.23	...	...	...

^a Uncorrected for extinction. Assumes $T_v = 2690$ K.

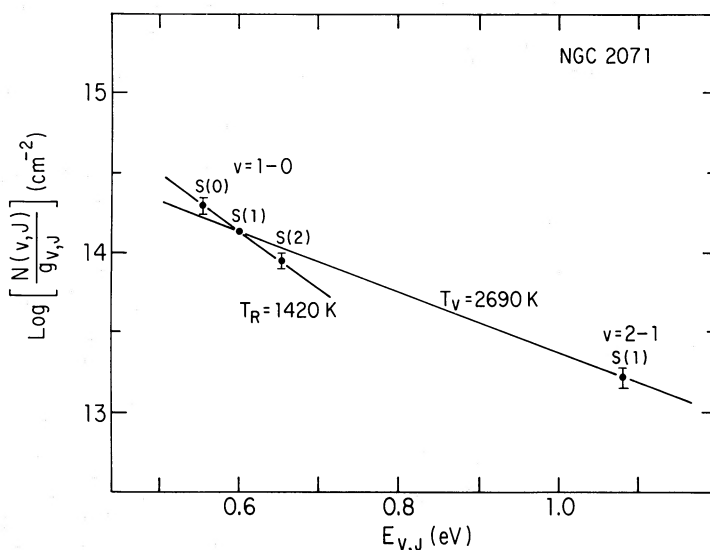


FIG. 5.—Plot of $\log [N(v, J)/g_{v,J}]$ vs. E used in deriving the excitation temperature of H₂ at the emission peak located at $\alpha_{1950} = 05^{\text{h}}44^{\text{m}}32^{\text{s}}.1$, $\delta_{1950} = 00^{\circ}21'40''$. The uncertainties refer to statistical and measurement errors. The fluxes used are uncorrected for extinction.

gas to the south of HH 12 may be confused with redshifted gas from the outflow associated with HH 7–11.

Herbig and Jones (1983) have measured the proper motions of several of the HH 12 knots. They find that all of the HH 12 knots appear to be moving roughly north with velocities of 60–240 km s⁻¹. Strom, Vrba, and Strom (1976) searched the NGC 1333 region for buried infrared sources at 2 μm , finding several sources in the HH 7–11 and HH 12 region. Of particular interest is SVS 12, located 30'' east of HH 12 with a K -band magnitude $m_K = 9.9$. Although its proximity to HH 12 makes it a possible candidate for the source which excites HH 12, the proper-motion measurements suggest that the kinetic energy responsible for the excitation of the HH object originates to the south of HH 12.

A remarkable recent CCD observation by Strom, Strom, and Stocke (1983) of the field surrounding HH 12 has revealed the presence of a very narrow optical jet linking HH 12 to an $m_K = 11.3$ mag star located 2' south (cf. Fig. 6). This feature is seen only in images taken through an H α filter and not in the adjacent continuum. The jet is $\sim 6''$ wide and exhibits at least two bends before connecting with the southern edge of HH 12.

We carried out a deep K -band survey of a $3' \times 6'$ field centered slightly to the south of HH 12 in order to locate all stars with K magnitude greater than ~ 13 . Ten objects in this category were found, several of which have been discussed in the literature (see notes to Table 2). In Table 2 we list the positions and broad-band J , H , K , and L magnitudes we obtained for these sources. Most of the infrared sources are visible as faint ($m_V \approx 19$ mag) stars on optical photographs.

ii) Molecular Hydrogen Observations

Simon and Joyce (1983) have detected H₂ $v = 1-0$ S(1) line emission from the vicinity of HH 12 and the vicinity of HH 7–11. We mapped the distribution of this line with $\sim 15''$ resolution over a 50 point grid toward HH 12. In Figure 6 we show the beam sizes and spatial sampling of our observations superposed on Strom, Strom, and Stocke's (1983) H α CCD image. The resulting contour map of the $v = 1-0$ S(1) line emission is shown in Figure 7. H₂ emission was detected only from the region of the optical condensations of the HH object. The

strongest S(1) line emission occurs at the northernmost tip of the optical nebulosity. The peak intensity is 6.3×10^{-5} ergs s⁻¹ cm⁻² sr⁻¹, comparable to the peak intensities in NGC 2071. The total detected S(1) line luminosity is $\sim 6.3 \times 10^{-3} L_{\odot}$, uncorrected for extinction. Assuming an excitation temperature of 2000 K, the total column density of hot H₂ at the peak is 1.88×10^{17} cm⁻². Our limit on the H₂ S(1) line emission from the jet is $< 5 \times 10^{-21}$ W cm⁻².

The Herbig-Haro object HH 6 lies about 6' to the east of HH 12. A compact 6 cm radio continuum source was recently found by Snell and Bally (1986) to coincide with this nebulosity. We found weak H₂ $v = 1-0$ S(1) line emission in the immediate vicinity of the HH object. Although we observed 11 positions surrounding the HH object (see Fig. 8), only those observations in which the 15'' aperture contained HH 6 show an emission line. The peak intensity is 2.0×10^{-5} ergs s⁻¹ cm⁻² sr⁻¹. We conclude that the molecular hydrogen emission is confined to a $\sim 20''$ region centered on HH 6 and the compact radio continuum source.

TABLE 2
POSITIONS AND PHOTOMETRY OF 2 MICRON SOURCES
DETECTED NEAR HH 12

α_{1950}	δ_{1950}	Previous Identification	J	H	K	L
3 ^h 25 ^m 50 ^s .9	31°08'10"	SVS 11 ^a ...	12.11	10.51	9.77	8.63
3 25 51.3	31 09 36	... ^b	...	...	10.08	...
3 25 51.6	31 12 14	...	...	...	11.99	...
3 25 52.7	31 07 46	Star 107 ^c ...	...	11.64	11.28	...
3 25 53.4	31 04 01	...	...	...	9.69	...
3 25 53.6	31 11 36	...	...	...	10.68	...
3 25 55.5	31 10 11	SVS 12 ^a ...	13.74	11.80	9.83	7.84
3 25 57.7	31 11 29	...	...	...	9.18	...
3 25 58.0	31 05 47	...	...	...	9.58	...
3 25 59.7	31 06 23	...	...	...	9.85	...

^a Strom, Vrba, and Strom 1976. (See also Cohen and Schwartz 1980, 1983.)

^b See also Cohen and Schwartz 1980.

^c Strom, Strom, and Stocke 1983.

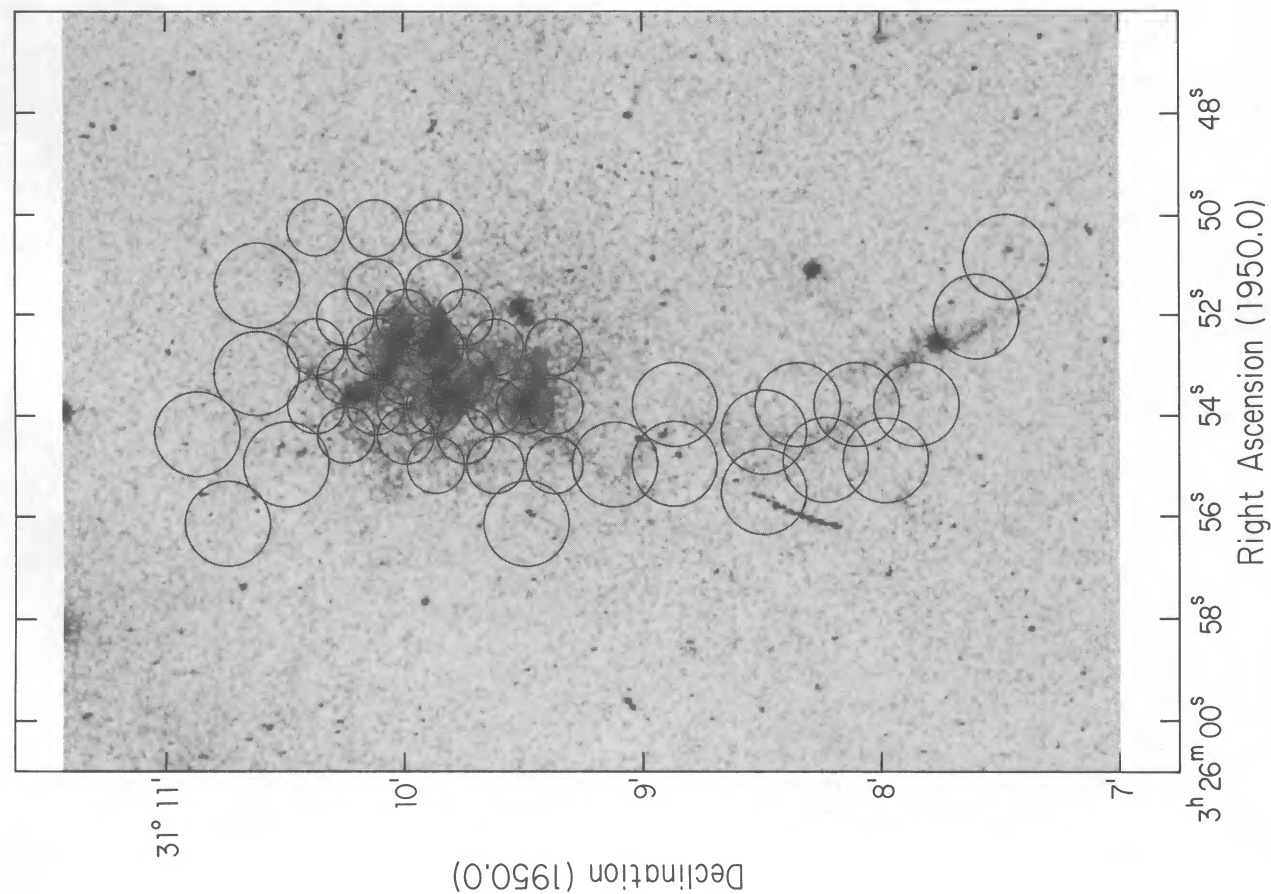


FIG. 6

FIG. 6.—Large circles show aperture sizes ($15''$ and $21''$) and spatial sampling of the $v = 1-0$ S(1) line observations used to construct the map in Fig. 7. They are superposed on an H α CCD image of the HH 12 region from Strom, Strom, and Stocke (1983).

FIG. 7.—Contours of the molecular hydrogen emission in the $v = 1-0$ S(1) transition toward HH 12. Contour levels are 6.0, 4.5, 2.9, and 1.3×10^{-5} ergs $\text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$. Plus signs indicate some of the μm sources for which photometry was obtained as part of this study (see Table 2). Designations 11, 12, and 107 refer to identifications of these sources by Strom, Strom, and Stocke (1983). The linear scale assumes a distance of 350 pc (Herbig and Jones 1983).

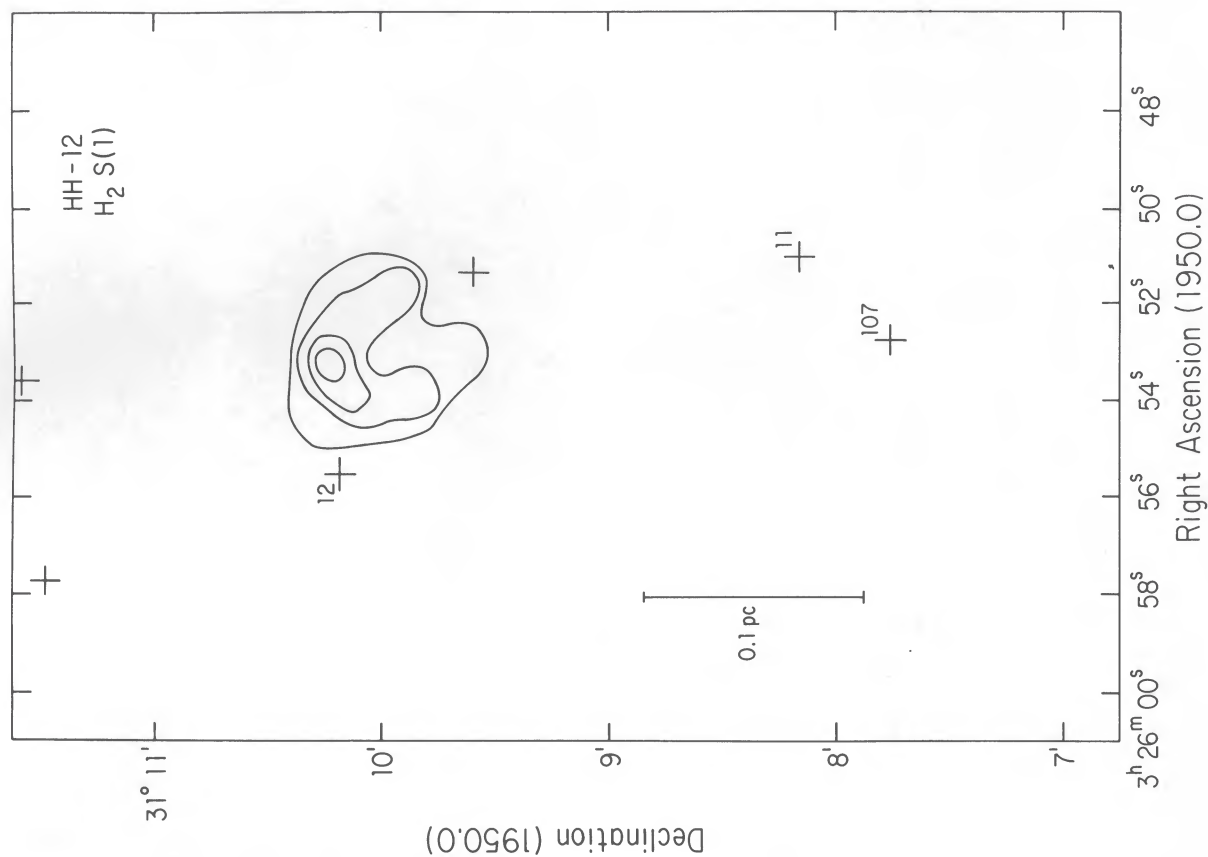


FIG. 7

TABLE 3
H₂ S(1) LINE SEARCH IN OTHER GALACTIC SOURCES

SOURCE	POSITION		NUMBER OF POINTS SEARCHED	NUMBER OF POINTS DETECTED	$(\Delta\alpha, \Delta\delta)$	FLUX ($\times 10^{-20}$ W cm $^{-2}$)
	α_{1950}	δ_{1950}				
Mon R2	06 ^h 05 ^m 22 ^s .0	-06°22'25"	10 ^a	3	(-45", 45") (-60, 30) (-75, 15)	1.6 $\pm$ 0.5 1.7 $\pm$ 0.6 1.3 $\pm$ 0.5
NGC 2264 ^b	06 38 25.0	09 32 12	5 ^c	1	(-60, 0) ^d	2.0 $\pm$ 0.7
R Mon ^b	06 36 25.0	08 46 00	2	0		< 6
Serpens ^b (H ₂ O) ..	18 27 24.42	01 12 39.7	11	0		< 2
GGD 29 ^b	18 29 09.5	01 15 44.18	5	0		< 2
G45.07 ^b	19 11 00.41	10 45 43	1	0		< 2

^a Other points searched are (0", 45"), (-15", 15"), (15", -15"), (30", -30"), (-30", -30"), (15", 15"), (-75", 75"); a 21" aperture was used.

^b A 32" aperture was used.

^c Other points searched are (0", 0"), (30", 0"), (60", 0"), (0", -60").

^d Simon 1985 detected S(1) line flux of 4.0×10^{-20} W cm $^{-2}$ (3 σ) at a position 15" south of this position.

c) Other Sources

We searched a number of other star-forming regions and three external galaxies for the H₂ S(1) line. Our results are summarized in Tables 3 and 4.

We report a new detection of H₂ emission from the bipolar flow source Mon R2. We found $v = 1-0$ S(1) line emission at a level of 2.0×10^{-5} ergs s $^{-1}$ cm $^{-2}$ sr $^{-1}$ at three positions approximately 1' to the northwest of IRS 3. The emission region appears to be at least 60" in extent, but because of limited time we were unable to map it. We have a tentative detection (3 σ) of S(1) line emission at a level of 1.0×10^{-5} ergs s $^{-1}$ cm $^{-2}$ sr $^{-1}$ at a position 60" west of NGC 2264.

Attempts to find S(1) line emission from sources lying close to the first quadrant of the galaxy (Serpens, GGD 29, G45.07)

TABLE 4
H₂ S(1) LINE SEARCH IN GALAXIES

Source	Continuum Flux ^a S_{λ} (W cm $^{-2}$ μ m $^{-1}$)	H ₂ S(1) Line Flux S_{λ} (W cm $^{-2}$)
NGC 2992	$(7.14 \pm 0.2) \times 10^{-18}$	$(1.4 \pm 1.0) \times 10^{-20}$
NGC 4321 (M100)	$(7.8 \pm 0.2) \times 10^{-18}$	$(1.8 \pm 1.0) \times 10^{-20}$
NGC 4151	$(1.68 \pm 0.02) \times 10^{-17}$	$(1.7 \pm 1.0) \times 10^{-20}$

^a Flux in a 15" circular aperture, centered on the position of peak brightness, which in all cases coincided with the visual position of the nucleus.

proved to be extremely difficult because of the very large number of bright 2 μ m sources, presumably background stars obscured at visual wavelengths. These stars, when falling close to the edge of the aperture, during either the "on" or the "reference" portion of the chopping cycle, provide an undetermined and variable source of background noise, the amplitude of which can vary with slight variations in pointing or seeing. Unchopped mapping, or frequency switching, under very stable observing conditions may alleviate these problems.

The S(1) line fluxes measured for the three galaxies we observed, NGC 2992, NGC 4321 (M100), and NGC 4151, provide only upper limits, since the values are less than 2 σ . The standard deviation σ is computed from the fluctuations of the measured numbers.

IV. DISCUSSION

a) The Gap in NGC 2071

One of the striking features of the H₂ map presented in Figure 1 is the discontinuity of the emission southwest of the infrared cluster. This gap in the emission can be interpreted in two ways: (1) The molecular hydrogen emission is formed in two distinct emission regions with no emission generated in the gap. (2) There is a region of enhanced extinction in front of the H₂ emission zone southwest of the infrared cluster producing the gap by extinction. The first model seems somewhat arbitrary, since the millimeter-wavelength tracers of the high-velocity flow show a continuous ridge of emission from the infrared cluster to the southwest. In both the ¹²CO line and the CS lines more high-velocity gas is seen in the redshifted lobe than in the blueshifted lobe. Both of these species show contin-

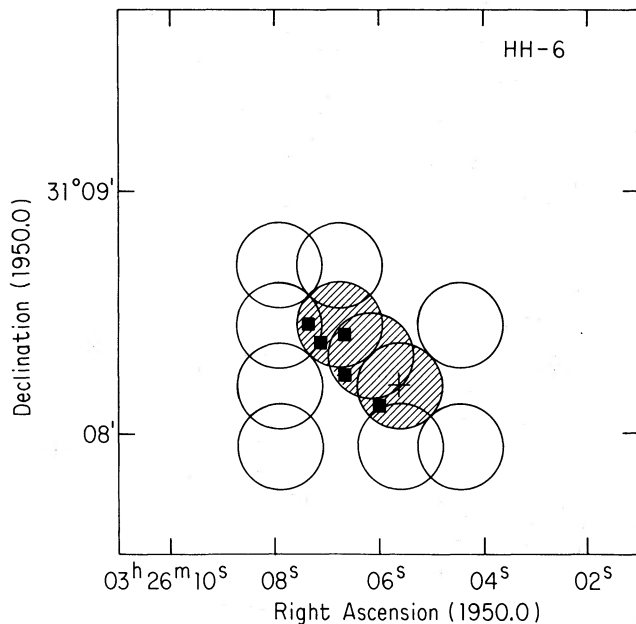


FIG. 8.—Map of the H₂ $v = 1-0$ S(1) line emission toward HH 6. Hatched circles indicate positions where emission was detected, at levels of (from northeast to southwest) 1.5, 1.7, and 1.2×10^{-20} W cm $^{-2}$ in a 21" beam. Open circles indicate nondetections (rms = 0.3×10^{-20} W cm $^{-2}$). Filled squares mark condensations in the optical nebula associated with HH 6. The plus symbol indicates a 6 cm VLA source detected by Snell and Bally (1986).

uous, smoothly distributed emission in the redshifted lobe observed to the southwest of the infrared cluster. A lack of radio emission over a $1'$ region would be apparent even with $1'$ telescope beams.

Several arguments support interpretation of the gap as an obscuration feature superposed on a more uniform emission source. Measurements of the column densities of ^{13}CO , C^{18}O , and CS indicate that the total column density of H_2 in the direction of the core of the NGC 2071 molecular cloud lies in the range $N(\text{H}_2) = 6 \times 10^{22}$ to $2 \times 10^{23} \text{ cm}^{-2}$ (Bally 1982). These determinations are based on the assumption that the excitation temperature for these species lies in the range $20 \text{ K} < T_{\text{ex}} < 35 \text{ K}$ and that the opacities of these species are low. The more recent data of Snell *et al.* (1984) support these assumptions. If the $S(1)$ line emitting gas lies halfway into the cloud, then half of this column density lies in front of the source. The extinction at $2 \mu\text{m}$ from this material is therefore expected to be in the range $A_{2.2} = 2\text{--}4 \text{ mag}$ (assuming $A_{2.2} = 0.1A_v$ and $N(\text{H}) = 5 \times 10^{21} A_v$).

The dense gas in the NGC 2071 cloud appears to be confined to a ridge that is oriented in a southeast-northwest direction, orthogonal to the outflow axis of the bipolar flow. This effect is seen in the distribution of CS, NH_3 , and C^{18}O (Bally 1982; Schwartz, Waak, and Smith 1983; Torrelles *et al.* 1983; Takano *et al.* 1984). It has been suggested that the high-velocity outflow breaks out of the dense cloud core in the direction where the gas density gradient drops at a maximum rate. This happens in a direction orthogonal to the orientation of the dense ridge. If the bipolar outflow axis is orthogonal to the sheet of dense gas responsible for the emission by large dipole moment molecules, then the blueshifted portion of the flow lies in front of the dense sheet and is not obscured by it. On the other hand, the redshifted part of the flow lies behind the dense sheet, and its dust content can obscure the near-infrared emission from this part of the flow. The observed gap in the $\text{H}_2 S(1)$ line emission lies in the region where a dense foreground sheet of gas is expected to cause heavy obscuration. The $1'$ thickness of the gap matches the extent of the region in which the high-excitation molecules are observed. In fact, the high-resolution $J = 1\text{--}0$ CS map of Takano *et al.* (1984) shows a secondary emission peak which falls precisely in the region of the gap in H_2 emission.

In conclusion, the gap seen in the H_2 emission associated with the redshifted part of the flow provides additional evidence for the existence of a dense sheet of gas orthogonal to the bipolar outflow in NGC 2071. The expected extinction ($2\text{--}4 \text{ mag}$ at $2.2 \mu\text{m}$) can attenuate the $S(1)$ line by a factor between 6 and 40, sufficient to explain the observations.

b) Excitation of the H_2 Emission

Before the morphology of the $S(1)$ line emission can be interpreted, a line formation mechanism for this line must be invoked. Studies of the brightest known source of near-infrared H_2 line emission, the core of the Orion molecular cloud, indicate that these lines are excited when highly supersonic ($v_s > 10 \text{ km s}^{-1}$) shocks impact dense [$n(\text{H}_2) > 10^5 \text{ cm}^{-3}$] molecular gas (Kwan 1977; London, McCray, and Chu 1977; Hollenbach and Shull 1977). Since the line widths seen in the near-infrared lines exceed 100 km s^{-1} in Orion and in NGC 2071, several variations of this basic model have been constructed. Chernoff, Hollenbach, and McKee (1982) and Draine and Roberge (1982) argue that the dense gas contains a magnetic field. The shock wave becomes a magnetohydrodynamic

(MHD) shock in which the postshock gas is accelerated more gently than in a hydrodynamic shock of equivalent speed. The lower velocity of collisions in an MHD shock ensures the survival of H_2 even at postshock velocities in excess of 30 km s^{-1} , where H_2 in a hydrodynamic shock dissociates. The precise morphology of the shock waves is not specified by these theories. The shocks may occur where a high-velocity outflow from a central source encounters ambient cloud material. Alternatively, the radiating shocks may occur within dense clumps entrained in the outflow. In this picture the radiation occurs on the upwind side of the lumps, where the wind responsible for lump acceleration delivers its momentum. In the discussion which follows, the important point is that the H_2 emission is a tracer of the region where the high-velocity outflow from a central source deposits its kinetic energy. Species such as H_2 , which are excited in the shock, radiate this energy away, allowing us to measure the quantity of deposited kinetic energy.

The temperature where the H_2 line formation occurs is found to be in the range $(1\text{--}3) \times 10^3 \text{ K}$ (see Fig. 5 and, for other sources, Beckwith *et al.* 1978; Fischer, Righini-Cohen, and Simon 1980; Shull and Beckwith 1982). At this temperature, the dominant coolant in a cloud is molecular hydrogen (Shull and Hollenbach 1978). At temperatures under 500 K , rotational transitions of abundant molecules, fine-structure lines of neutral metals, and dust grains provide cooling. Above 5000 K , radiation by ionic species becomes important. Most of the kinetic energy of the wind responsible for the high-velocity outflows is converted into radiation by H_2 molecules. The observed $S(1)$ line luminosity is a rough indicator of the total H_2 line luminosity. If the temperature and the extinction are known, then the total molecular cooling rate is related to the observed $S(1)$ line intensity by

$$L_{\text{TOT}} = (I_{\text{TOT}}/I_{S(1)})L_{S(1)} \times 10^{A_{2.2}/2.5},$$

where $I_{\text{TOT}}/I_{S(1)} = 10$ for $T = 2000 \text{ K}$ (cf. Scoville *et al.* 1982). For NGC 2071, we find $L_{\text{TOT}} \approx 10.8 L_{\odot}$.

V. INTERPRETATION: A JET MODEL FOR BIPOLAR OUTFLOWS

The radio, infrared, and optical evidence indicates that high-velocity outflows surrounding young stars are collimated into a bipolar ejection pattern. The H_2 map of Figure 1 suggests that the collimation of NGC 2071 is excellent. As argued above, the H_2 map indicates the location of shocks where the kinetic energy of the outflow is converted into radiation. The morphology of the emission region indicates that the outflow is confined to a channel less than $1'$ wide and more than $2'$ long on either side of the source.

In HH 12, the H_2 emission and the HH object itself are located at the end of a filament of nebulosity which intersects the reddened image of a star $2'$ to the north (Strom, Strom, and Stocke 1983). The filament may mark the presence of a flow channel through which mechanical energy is transported from the star to HH 12 itself. The observations suggest that both NGC 2071 and HH 12 may contain jets that act as conduits for the transport of mechanical energy from a source to locations where it is dissipated in luminous shock waves.

We model the jet as a collimated, pressure-confined flow with a particle density n_j and with velocity V_j in a channel of radius R_j . We assume that the jet contains a wind blowing from a young star and represents a mass-loss rate $\eta \dot{M}_*$, where η is the fraction of the stellar wind entering the jet (for a bipolar flow, $\eta = 0.5$). Jet formation may result from the anisotropic

ejection of matter from the vicinity of the star, or from the collimation of an initially isotropic wind by a circumstellar structure, such as a disk, which forms a nozzle (cf. Königl 1982). We will not address the mechanisms leading to the formation of the jet; we take it as an observed fact that the outflows are highly collimated.

If $\eta\dot{M}_*$ and V_j represent the amount and flow velocity of gas flowing through the jet, then the mechanical luminosity of the jet (the flux of kinetic energy per second) is

$$L_M = \frac{1}{2}\eta\dot{M}_* V_j^2. \quad (1)$$

We assume that the jet is pressure-confined so that the diameter of the jet is determined by the balance between the internal pressure of the jet and the pressure of the surrounding molecular cloud. The pressure can be represented as the sum of thermal and magnetic pressures. If equipartition holds and the magnetic pressure is proportional in magnitude to the thermal pressure, then the condition of pressure balance can be written as

$$n_0 T_0 = n_j T_j, \quad (2)$$

where n_0 and T_0 represent the number density and temperature of the confining cloud, and n_j and T_j represent these parameters in the jet. For flow down a cylinder,

$$n_j = \frac{\eta\dot{M}_*}{\pi\mu m_H R_j^2 V_j}, \quad (3)$$

where μ is the mean molecular weight and R_j is the jet radius. Combining equations (1), (2), and (3) results in expressions for $\dot{M}_*$ and V_j in terms of the parameters R_j and L_M :

$$\dot{M}_* = \frac{1}{\eta} (2^{1/2} \pi \mu m_H)^{2/3} \left(\frac{n_0 T_0}{T_j} \right)^{2/3} R_j^{4/3} L_M^{1/3}, \quad (4a)$$

$$V_j = \left(\frac{2}{\pi \mu m_H} \right)^{1/3} \left(\frac{L_M T_j}{n_0 T_0} \right)^{1/3} R_j^{-2/3}. \quad (4b)$$

Most of the energy of the jet is dissipated at the leading edge of the flow, the jet terminus, where a radiative shock converts kinetic energy into radiation. From momentum conservation,

the jet terminus moves into the molecular cloud at a velocity roughly given by

$$V_t = \left(\frac{n_j}{n_0} \right)^{1/2} V_j \approx \left(\frac{T_0}{T_j} \right)^{1/2} V_j.$$

Since most of the kinetic energy is converted into radiation, the total radiated luminosity of the jet terminus provides a measure of the jet mechanical luminosity. Some fraction of the radiation emerges in the infrared emission lines of the H₂ molecule; much of the rest is emitted by optical emission lines which are subsequently absorbed by dust and reradiated in the far-infrared. We assume that $L_M = f L(\text{H}_2)$, where the constant of proportionality f measures the ratio of the luminosity emitted by all transitions of H₂ and the luminosity of all other energy dissipation processes. Since the power emitted by the H₂ lines and that emitted by the optical lines are similar, we take $f = 2$. Detailed considerations of the shock are required for a more accurate estimation of f .

In order to use equations (4a) and (4b), estimates for the various parameters are required. Table 5 summarizes the values we chose for our sources and for Orion A which we consider for comparison purposes. We estimate a kinetic temperature of 3000 K for the jet, based on the constraints imposed by the detectability of H α in the HH 12 jet and the observed H₂ temperature in NGC 2071 and in Orion. Since Herbig-Haro object spectra do not indicate large electron abundances, $T < 10^4$ K. At higher temperatures, the O I, N II, and S II lines typically observed in low-excitation HH spectra would disappear, with most of the O, N, and S in a higher ionization state. Admittedly, the jet temperature is highly uncertain and the value picked is a crude estimate. The ambient cloud properties can be derived from millimeter-wavelength observations of transitions of CO, CS, H₂CO, and other molecules. The values we use are derived from the references given in Table 5. The estimate of the jet mechanical luminosity is obtained by assuming that $f = 2$ and that the total molecular hydrogen luminosity is 10 times the S(1) line luminosity. We use the extinction-corrected S(1) line flux, integrated over the projected area of each source to derive the S(1) line luminosity. For Orion, values quoted in the literature are used. For HH 12, we have assumed $A_v = 23$ mag (cf. Strom, Grasdalen, and Strom 1974).

TABLE 5
VALUES OF PARAMETERS USED TO ESTIMATE MASS-LOSS RATE AND WIND VELOCITY OF OUTFLOW SOURCES

PARAMETER	HH 12		NGC 2071		ORION A	
	Value	Reference	Value	Reference	Value	Reference
n_0 (cm ⁻³)	3×10^4	1	3×10^4	5	2×10^5	
T_0 (K)	25	1	35	5	80	
T_j (K)	3×10^3	2	3×10^3	2	3×10^3	2
$L(\text{H}_2)$ ($L_\odot$)	0.52	2	10.8	2	200	6
L_M (ergs s ⁻¹) ^a	4×10^{33}	2	8×10^{34}	2	1.6×10^{36}	2
R_j (cm) ^b	1.6×10^{16}	3	1.7×10^{17}	2	1.0×10^{17}	7
$\dot{M}_j$ ($M_\odot$)	0.1	4	9.7	5	8.2	5
V_j (km s ⁻¹)	15	4	8.4	5	19.5	5
R_{max} (pc)	0.1	4	0.14	5	0.03	5

^a We assume $L_M = f L(\text{H}_2)$, with $f = 2$.

^b Assumes distance of 350 pc for HH 12 and 500 pc for Orion and NGC 2071. The jet diameters are taken to be 6" for HH 12, 45" for NGC 2071, and 30" for Orion A.

REFERENCES.—(1) Loren, Evans, and Knapp 1979; Lada *et al.* 1974. (2) This paper. (3) Strom, Strom, and Stocke 1983. (4) Edwards and Snell 1984. (5) Snell *et al.* 1984. (6) Beckwith *et al.* 1983. (7) Beckwith *et al.* 1978.

The jet radii are deduced from the observed morphology of each source. From Figure 1 we estimate that the diameter of the NGC 2071 jet is 45", similar to the value deduced from the $J = 2-1$ CO map of Snell *et al.* (1984). For HH 12, we use the apparent width of the H α filament seen by Strom, Strom, and Stocke (1983); this is 6". For Orion we use the apparent minor-axis dimension of the H $_2$ as mapped by Beckwith *et al.* (1978).

Each of the parameters is uncertain by some factor. The density estimates may be off by a factor of 2, with a possible 50% error in the ambient temperature. The jet temperature is most uncertain; it could be wrong by a factor of 4. The jet radii and H $_2$ luminosities are probably accurate to a factor of 2. For $\mu = 2$ and $\eta = 0.5$, equations (4a) and (4b) can be evaluated to give

$$\dot{M}_* = 1.208 \times 10^{-15} \left(\frac{n_0 T_0}{T_j} \right)^{2/3} R_j^{4/3} L_M^{1/3} \quad (\text{gm s}^{-1}),$$

$$V_j = 5.755 \times 10^7 \left(\frac{L_M T_j}{n_0 T_0} \right)^{1/3} R_j^{-2/3} \quad (\text{cm s}^{-1}).$$

Table 6 summarizes the results of these computations. Figure 9 is a plot of the $(\dot{M}_*, V_j)$ -plane on which we plot the mass-loss parameters derived from the H $_2$ observations of NGC 2071, HH 12, and the Orion molecular flows, along with error boxes representing the variation of the derived values as the cloud and jet parameters are allowed to vary over their permitted values. Also plotted (*dashed lines*) are the constraints on the mass-loss parameters derived from millimeter-wavelength CO observations. These constraints are obtained from the total mass of the moving material M_f , its typical or average velocity V_f , and the flow dynamical time scale, $\tau_D = R_{\text{max}}/V_f$, from

$$\dot{M}_* = \frac{M_f V_f^2}{R_{\text{max}}} \frac{1}{V_j}.$$

The adopted values for the CO parameters are listed in Table 5; the parameters for Orion and NGC 2071 were taken from Snell *et al.* (1984), while the parameters for HH 12 were obtained from Edwards and Snell (1984).

As can be seen from Figure 9, the best estimates for the mass-loss parameters derived from the H $_2$ observations fall close to the lines representing the constraints derived from the CO data. The outflow velocities fall between 100 and 400 km s $^{-1}$, which includes the range found for the proper motions of most Herbig-Haro objects.

The mass-loss parameters derived from the H $_2$ observations place strong constraints on the nature of the Herbig-Haro nebulosities in HH 12. The proper-motion vectors for the brightest optical knots have values around 150–250 km s $^{-1}$, close to the wind velocity computed from the H $_2$ observations. The optical emission must arise in instabilities in the wind just prior to encountering the jet terminus. If the optical emission were formed in the postshock gas, it would have a velocity $(n_j/n_0)^{1/2} V_j$, which is about 10% of the jet velocity (~ 20 km s $^{-1}$), contrary to both the spectroscopic and the proper-

TABLE 6

COMPUTED MASS-LOSS PARAMETERS FOR THREE OUTFLOWS

Parameter	HH 12	NGC 2071	Orion
$\dot{M}_* (M_\odot \text{ yr}^{-1})$	4.6×10^{-7}	3.7×10^{-5}	3.0×10^{-4}
$V_j (\text{km s}^{-1})$	228	115	179

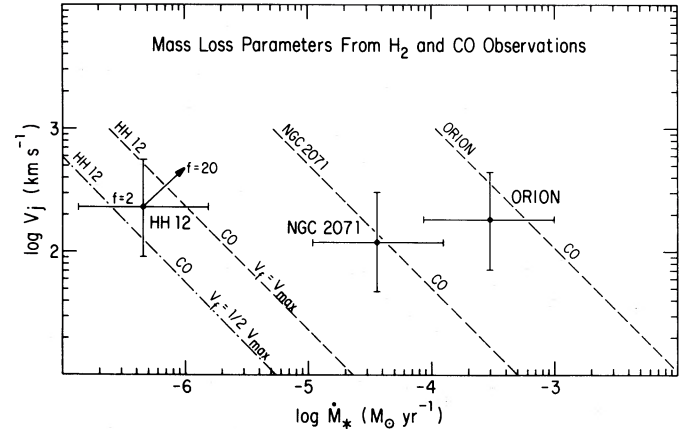


FIG. 9.—Constraints on mass-loss rate and wind velocity obtained from H $_2$ observations (points with error bars) and CO observations (*dashed lines*) for the outflows in HH 12, NGC 2071, and Orion. The parameter f gives the ratio of the mechanical luminosity of the jet to the H $_2$ luminosity. For the plotted points we assume $f = 2$. The arrow labeled " $f = 20$ " illustrates that a tenfold increase in the parameter f changes the estimated wind parameters by a factor of about 2. V_f is the typical or average velocity of the CO emitting gas.

motion velocities derived for HH objects. The millimeter-wavelength (and H $_2$) emission lines are probably associated with postshock, swept-up cloud material, while the optical emission is probably formed close to the point where the wind passes through the reverse shock.

VI. CONCLUSIONS

Near-infrared emission in the vibrationally excited lines of molecular hydrogen appears to be a common property of molecular clouds containing high-velocity outflows. Both very energetic outflows associated with massive, luminous, newly formed stars, and less energetic outflows associated with low-mass, T Tauri-type stars, exhibit near-infrared H $_2$ emission lines. Our mapping of the $S(1)$ line emission in NGC 2071 and HH 12 delineates the location of shock fronts in these outflows. In NGC 2071, the outflow is shown to be confined to two narrow, oppositely directed jets of gas emerging from the recently formed cluster of stars. The strongest of five emission peaks in this source occurs at the outer boundary of the high-velocity flow region mapped in CO. A gap in the H $_2$ emission located directly to the southwest of the NGC 2071 infrared cluster, toward the receding part of the flow, may indicate the presence of a dense sheet of gas whose extinction at 2 μ m is several magnitudes. This observation provides additional supporting evidence for the existence of a massive circumstellar disk around NGC 2071, the portion lying between us and the receding part of the flow providing the extinction blocking the molecular hydrogen from our view. In HH 12 the $S(1)$ line emission is closely correlated with the optical Herbig-Haro nebulosity, and peaks in the north; proper-motion measurements indicate that the HH object clumps are moving northward. In both outflows, the molecular hydrogen emission delineates the location where the kinetic energy of the high-velocity outflow is being converted into thermal energy by a shock wave and is radiated away.

The molecular hydrogen luminosity provides an estimate of the mechanical luminosity of the wind driving the outflow. If the width of the outflowing jets is determined by pressure balance between the jet and the surrounding molecular cloud, then the observed thickness of the jet can be used to constrain

the internal pressure of the wind. Combining the mechanical luminosity derived from H₂ measurements with the internal pressure leads to an estimate of the mass-loss parameters of the source of the outflow. In NGC 2071, these parameters ($\dot{M}_* \sim 3.7 \times 10^{-5} M_\odot \text{ yr}^{-1}$, $V_j \sim 115 \text{ km s}^{-1}$) are in approximate agreement with constraints derived from CO measurements. For HH 12, the values deduced from the H₂ observations ($\dot{M}_* \sim 4.6 \times 10^{-7} M_\odot \text{ yr}^{-1}$, $V_j \sim 228 \text{ km s}^{-1}$) are consistent with the mass-loss rate and wind velocity expected of T Tauri stars.

We have demonstrated that observations of the 2 μm lines of molecular hydrogen provide a powerful probe of the morphology and energetics of outflows associated with stellar birth.

The relatively high angular resolution presently available at this wavelength, combined with the ability of the H₂ lines to detect only very hot molecular gas, make 2 μm studies of energetic phenomena in molecular clouds particularly valuable.

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JOHN BALLY: AT & T Bell Laboratories, HOH L245, Holmdel, NJ 07733

ADAIR P. LANE: Astronomy Department, Boston University, 725 Commonwealth Avenue, Boston, MA 02215