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HIGH VELOCITY H_2 LINE EMISSION IN THE NGC 2071 REGION

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ABSTRACT

Emission in the $v = 1 \rightarrow 0$ $S(1)$ line of H_2 at 2.12 μm has been measured at 20 km s^{-1} resolution in the vicinity of the microwave maser and infrared continuum sources north of NGC 2071. The line profile observed near the peak of the extended H_2 emission region has full width at zero intensity of ~ 100 km s^{-1}, with a prominent blue wing. The NGC 2071 region thus represents the second detection, after OMC-1, of high velocity H_2 emission in a region showing signs of ongoing star formation. The width of the line may result from a supersonic outflow of gas from within the molecular cloud. By analogy to the core of OMC-1, with which the NGC 2071 region has several characteristics in common, we suggest that the source of the high velocity outflow is an intense stellar wind from an embedded infrared object.

Subject headings: infrared: sources — infrared: spectra — interstellar: molecules — shock waves

I. INTRODUCTION

The Lynds 1630 dark cloud is a site of recent star formation, as evidenced by the presence within its boundaries of Hα emission stars, H-H objects, reflection nebulae, obscured infrared sources, and dense CO condensations (see Strom, Strom, and Vrba 1976 and references therein). Of particular interest is a region about 4′ north of the reflection nebula NGC 2071, where Strom *et al.* found a bright, heavily obscured, near-infrared source (hereafter SSV 41) in their 2 μm survey of the dark cloud. Located near SSV 41 are a type I OH maser (Johansson *et al.* 1974), an H_2O maser (Schwartz and Buhl 1975; Genzel and Downes 1979), and a bright 10 μm and far-infrared source (Evans *et al.* 1979; Harvey *et al.* 1979). CO observations of the maser/infrared source region have been reported by a number of groups (Tucker, Kutner, and Thaddeus 1973; Gilmore 1980; Phillips *et al.* 1981; Loren *et al.* 1981; White and Phillips 1981). Recently, Bally (1981) has detected faint high velocity wings on the ^{12}CO $J = 1 \rightarrow 0$ profile (full width at zero intensity of 70 km s^{-1}); these provide evidence for a high velocity molecular flow in this region.

Both Simon and Joyce (1981) and Bally and Lane (1981) have detected emission from H_2 in the vicinity of SSV 41. According to Simon and Joyce's $v = 1 \rightarrow 0$ $S(1)$ line map of the region (at 34″ resolution), the H_2 emission region is roughly 1′ × 1′ in size and centered near SSV 41. The only H_2 line source in a molecular cloud that previously has been studied at high spectral resolution is in the Orion Molecular Cloud (OMC-1), where the $S(1)$ line displays very wide wings (Nadeau and Geballe 1979, hereafter NG; Nadeau, Geballe, and Neugebauer 1981, hereafter NGN; Scoville *et al.* 1981). It is clearly of interest to study the kinematics of the excited H_2 in other molecular clouds and to determine how common the OMC-1 H_2 phenomenon is. In this *Letter*, we report measurements of the spatial distribution of the H_2 $S(1)$ line intensity in NGC 2071, spectroscopy with 20 km s^{-1} resolution of the $S(1)$ line at two positions, and a 10 μm map of the region near the H_2 emission peak.

II. OBSERVATIONS

Mapping and spectroscopy of the 2.1218 μm $v = 1 \rightarrow 0$ $S(1)$ line of H_2 were carried out at the NASA 3 m infrared telescope (IRTF) of the Mauna Kea Observatory in 1980 December. The measurements were made using a cold grating infrared spectrometer, which can be used in conjunction with a piezoelectrically scanned Fabry-Perot interferometer for high spectral resolution work. The instrumentation is described by Persson, Geballe, and Baas (1981). The vicinity of the H_2 peak detected by Simon and Joyce (1981) was searched using the grating spectrometer, with a circular entrance aperture 7″ in diameter and a resolving power of ~ 800 at the $S(1)$ line. The secondary mirror of the IRTF was chopped between the signal position and a reference position 60″ west for all the observations. The data clearly showed a peak in the $S(1)$ line flux over a region $\sim 10''$ in size located $\sim 10''$ southwest of SSV 41, sur-

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TABLE 1

NGC 2071 POSITIONS AND FLUX DENSITIES

Source	R.A. (1950) (05^h44^m)	Decl. (1950) (00°20′)	F_ν[a] (10 μm) (Jy)	Reference
H_2 spectrum	$31^s.2 \pm 0^s.2$	48″ ± 2″	...	a
IRS 1	30.6 ± 0.2	42 ± 1	18.9 ± 1.9	a
IRS 2	31.2 ± 0.2	48 ± 2	2.2 ± 0.4	a
IRS 3	30.6 ± 0.2	48 ± 2	1.4 ± 0.3	a
IRS 4	31.2 ± 0.2	54 ± 3	0.4 ± 0.1	a
SSV 41	31.4 ± 0.5	57 ± 7	...	b
OH 205.1–14.1	29.5 ± 0.9	30 ± 18	...	c
H_2O 205.11–14.11 ...	31.3 ± 0.4	48 ± 6	...	d

[a]This *Letter*.
[b]Strom, Strom, and Vrba 1976.
[c]Pankonin, Winnberg, and Booth 1977.
[d]Genzel and Downes 1979.

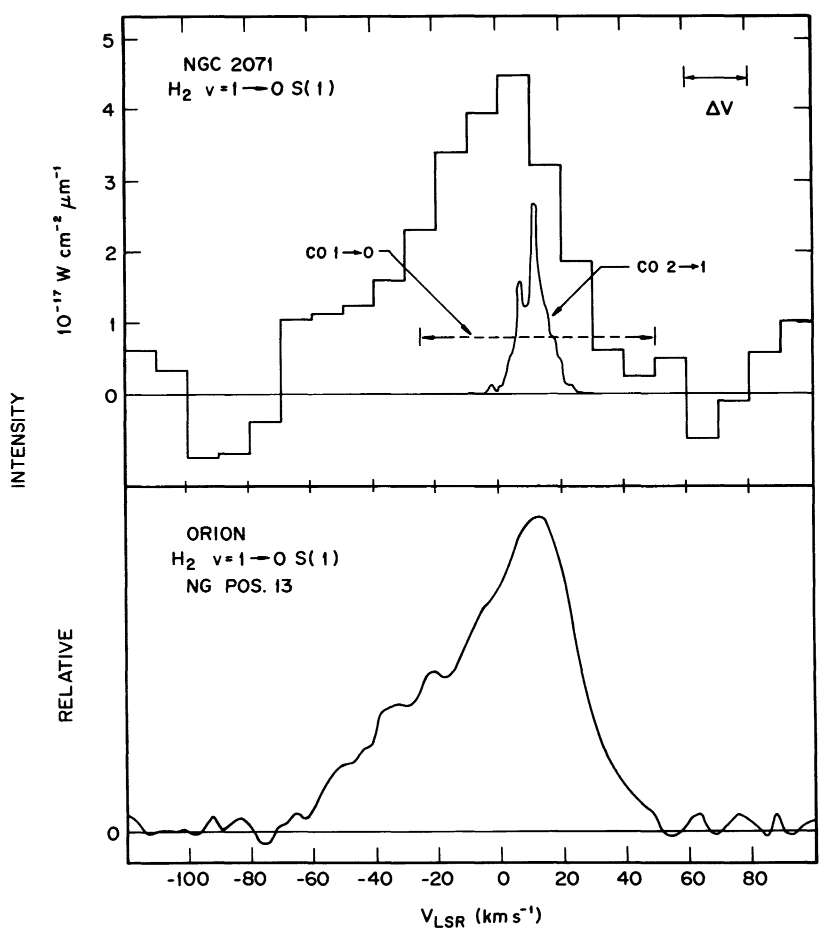

FIG. 1.—Spectrum of the $v = 1 \rightarrow 0$ $S(1)$ 2.12 μm line of H_2 toward the infrared source region north of NGC 2071. The line observed by NG in the KL Nebula in OMC-1, at their position 13, is shown for comparison. The FWHM velocity resolution ($\Delta V = 20$ km s^{-1} for both spectra) is also shown. For NGC 2071 the data were binned into 10 km s^{-1} intervals. The baseline was determined by averaging the data in 50 km s^{-1} intervals at each end of the spectrum. The CO $J = 2 \rightarrow 1$ profile is adapted from the work of Loren *et al.* (1981). The full extent of the emission in the CO $J = 1 \rightarrow 0$ line as measured by Bally (1981) is also shown.

rounded by flux extending over a region at least 40″ in diameter.

The Fabry-Perot interferometer was then inserted into the beam and a spectrum of the $S(1)$ line was obtained at the position of the peak H_2 line flux (see Table 1). The FWHM resolution of the interferometer was 20 km s^{-1} and the sweep amplitude was 300 km s^{-1}. Sums of 16 individual sweeps were stored in a microcomputer; velocity drifts between adjacent sums were continuously monitored and were always less than 3 km s^{-1}. The stored sums, which comprise a total of 3 hours of integration, were reregistered in velocity and combined to produce the final spectrum shown in Figure 1. The baseline was determined by averaging data in 50 km s^{-1} intervals at each end of the spectrum. The noise in the observed profile can be judged from the fit to this baseline over these two intervals. A second spectrum was obtained in 1 hour at a position 5″ southwest of the first spectrum; the line shape is the same as that shown in Figure 1 to within the uncertainties.

Flux calibration was obtained by observing stars of known 2.2 μm brightness; the resulting integrated $S(1)$ emission line intensity is $1.8 \pm 0.3 \times 10^{-20}$ W cm^{-2} in the 7″ diameter beam. Thus, the NGC 2071 source is approximately 40 times fainter than Peak 1 of the Orion H_2 line source (Beckwith *et al.* 1978; NG), which lies at the same distance as the NGC 2071 region.

The IRTF infrared photometer was used to map the spatial distribution of 10 μm radiation in the immediate vicinity of the H_2 emission peak. A grid of points spaced by 3″ was observed with a beam diameter of 5″.5, and with reference beam positions 60″ north and south. The resulting map (Fig. 2) shows that the H_2 emitting region contains at least three (faint) discrete sources in addition to the bright source discovered by Evans *et al.* (1979) and Harvey *et al.* (1979), but there is no clear evidence for extended emission. The positions and 10 μm flux densities of the sources are given in Table 1. Bally and Predmore (1981) have recently mapped the region at 5 GHz with the VLA. They find two faint compact H II regions which coincide with IRS 1 and IRS 3.

III. RESULTS AND DISCUSSION

The main result of this *Letter* is the wide and asymmetric velocity profile of the excited H_2 gas in the NGC 2071 region (Fig. 1). $S(1)$ line emission extends over a range of ~ 100 km s^{-1}, and the blueshifted side of the line is much stronger than the redshifted side. The peak

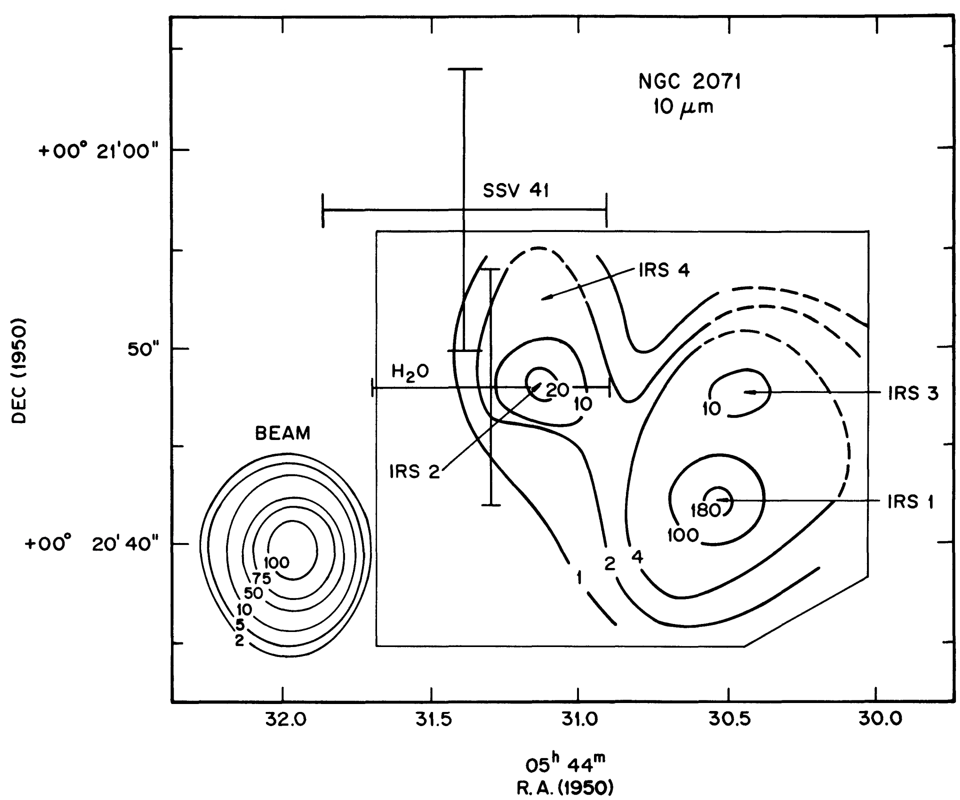

FIG. 2.—10 μm map of the NGC 2071 region. Positions of the Genzel and Downes (1979) H_2O maser and the measured beam size are shown. The individual sources are listed in Table 1.

of the $S(1)$ line occurs at $V_{LSR} = +5 \pm 10$ km s^{-1}, which is close to the $+10$ km s^{-1} velocity of the molecular cloud (Bally 1981). NGC 2071 is thus the second example, after OMC-1, of a molecular cloud source showing high velocity H_2 emission. The fact that the velocity extent of the H_2 is larger than that of the CO line (Bally 1981) may be due to a difference in sensitivity of the two techniques, or it could simply indicate that the H_2 line emission arises in a different part of the cloud.

The $S(1)$ line profile observed in the NGC 2071 region is similar to those observed by NG in OMC-1. The lower panel in Figure 1 shows NG's $S(1)$ spectrum at their position 13, obtained at essentially the same spectral resolution as the present measurement. Position 13 lies close to the center of the KL Nebula, where a number of luminous young objects are found. Although this particular OMC-1 spectrum most closely resembles the one seen in the NGC 2071 region, all of the H_2 spectra obtained near KL show the same general characteristics as position 13.

In OMC-1 the broad radio molecular line profiles, the pattern of proper motions of the high velocity masers, and the broad, asymmetric H_2 emission lines have been attributed to an outward flow of material from a central object, presumably one of the infrared cluster sources (Kwan and Scoville 1976; Zuckerman, Kuiper, Rodriquez-Kuiper 1976; NG; Downes *et al.* 1981; Genzel *et al.* 1981; Welch *et al.* 1981; Reid and Moran 1981). The present H_2 line spectroscopic data, together with the large velocity extent of the CO line wings (Bally 1981) and the existence nearby of several 10 μm sources, suggest a qualitatively similar model for the core of the NGC 2071 source. In OMC-1 the H_2 line emission is believed to arise in shock heated gas located near the interface of the flow and the surrounding molecular cloud, and also within the flow itself (NGN; Scoville *et al.* 1981). The details of the H_2 excitation mechanism are not clear, but the present results show that any mechanism proposed to explain the wide and asymmetric H_2 lines in OMC-1 must also work in NGC 2071, in spite of differences in physical properties between the two sources. Most notably these differences are that the intensities of the ^{12}CO line wings are much weaker in NGC 2071 but much more extended spatially (Bally 1981), the H_2 surface brightness is much lower in NGC 2071, and the bolometric luminosity of NGC 2071 is only 10^3 $L_\odot$ (Sargent *et al.* 1981) compared to 10^4–10^5 $L_\odot$ for the brighter objects within the infrared cluster of OMC-1 (Downes *et al.* 1981).

In OMC-1 the asymmetric H_2 line shapes (NG; NGN; Scoville *et al.* 1981) have been attributed to dust within the high velocity expanding flow, which selectively attenuates the red side of the line. NGN have shown that the amount of dust required to produce the H_2 line asymmetry is consistent with the column density of material inferred from the intensity of the high velocity wings of the $J = 1 \rightarrow 0$ ^{12}CO line. The corresponding wings observed by Bally (1981) toward NGC 2071 are quite symmetric at the position where our H_2 spectrum was obtained, but are at least 10 times fainter than in Orion. Therefore if the ^{12}CO high velocity wings are optically thin in both sources and measure the column density of dust along the line of sight through the H_2 emission region, then one would expect the NGC 2071 H_2 line profile to be considerably less asymmetric than it is. The explanation of this discrepancy seems likely to be that the geometrical distribution of gas and dust with respect to our line of sight is quite different in the two sources. This is also suggested by the large-scale pattern of a bipolar outflow of gas in NGC 2071 as seen in Bally's (1981) ^{12}CO map.

The widths of the H_2 lines suggest that the kinematics, or at least the maximum velocity extent of the flows, are similar in NGC 2071 and OMC-1. From this we infer that the ratios of momentum to density are similar in the high velocity flows of the two molecular clouds. The density of the high velocity material is probably lower in the core of NGC 2071 than in Orion, since the high velocity wings of the ^{12}CO line are considerably weaker, the source size larger, and the H_2 surface brightness is ~ 40 times fainter. The momentum input required of the central driving source is therefore likely to be lower in NGC 2071 than in Orion by a factor which is very uncertain, but probably $\gtrsim 10$.

The fact that the total luminosities of the embedded sources (see above) are in roughly the same ratio suggests that the flows might be radiatively driven by a wind from one of the compact 10 μm infrared sources. Such winds have been considered inadequate to explain the high velocity flows because the momentum in photons, L/c, is typically a factor of at least 50 too small (Zuckerman 1981; Lada and Harvey 1981). However, Solomon, Huguenin, and Scoville (1981) and Phillips and Beckman (1980) have suggested that a large infrared grain opacity close to the central power source can strongly trap the infrared radiation, and a large multiplication of the photon momentum imparted to the gas can be achieved.

It is doubtful that this mechanism can work for NGC 2071, because the luminosity of the embedded infrared source(s) is one to two orders of magnitude too small. According to Solomon *et al.*'s equation (3) and their subsequent discussion, the condition for a net outward acceleration is $L/L_\odot > 3 \times 10^3\ M/M_\odot$, where L and M are the luminosity and mass of the central source. Since $L \sim 10^3\ L_\odot$ in NGC 2071, $M < 0.33\ M_\odot$. We therefore conclude that some driving mechanism for the high velocity flows must be found other than radiatively driven winds.

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REFERENCES

Bally, J. 1981, paper presented at Symposium on Neutral Clouds near H II Regions: Dynamics and Photochemistry, Penticton, British Columbia.

Bally, J., and Lane, A. 1981, paper presented at Symposium on Neutral Clouds near H II Regions: Dynamics and Photochemistry, Penticton, British Columbia.

Bally, J., and Predmore, R. 1981, preprint.

Beckwith, S., Persson, S. E., Neugebauer, G., and Becklin, E. E. 1978, *Ap. J.*, **223**, 464.

Downes, D., Genzel, R., Becklin, E. E., and Wynn-Williams, C. G. 1981, *Ap. J.*, **244**, 869.

Evans, N. J., II, Beckwith, S., Brown, R. L., and Gilmore, W. 1979, *Ap. J.*, **227**, 450.

Genzel, R., and Downes, D. 1979, *Astr. Ap.*, **72**, 234.

Genzel, R., Reid, M. J., Moran, J. M., and Downes, D. 1981, *Ap. J.*, **244**, 884.

Gilmore, W. 1980, *A.J.*, **85**, 912.

Harvey, P. M., Campbell, M. F., Hoffman, W. F., Thronson, H. A., Jr., and Gatley, I. 1979, *Ap. J.*, **229**, 990.

Johansson, L. E. B., Hoglund, B., Winnberg, A., Nguyen-Q-Rieu, and Goss, W. M. 1974, *Ap. J.*, **189**, 455.

Kwan, J., and Scoville, N. Z. 1976, *Ap. J. (Letters)*, **210**, L39.

Lada, C. J., and Harvey, P. M. 1981, *Ap. J.*, **245**, 58.

Loren, R. B., Plambeck, R. L., Davis, J. H., and Snell, R. L. 1981, *Ap. J.*, **245**, 495.

Nadeau, D., and Geballe, T. R. 1979, *Ap. J. (Letters)*, **230**, L169 (NG).

Nadeau, D., Geballe, T. R., and Neugebauer, G. 1981, *Ap. J.*, **253**, in press (NGN).

Pankonin, V., Winnberg, A., and Booth, R. S. 1977, *Astr. Ap. Letters*, **58**, L25.

Persson, S. E., Geballe, T. R., and Baas, F. 1981, in preparation.

Phillips, J. P., and Beckman, J. E. 1980, *M.N.R.A.S.*, **193**, 245.

Phillips, T. G., Knapp, G. R., Huggins, P. J., Werner, M. W., Wannier, P. G., Neugebauer, G., and Ennis, D. 1981, *Ap. J.*, **245**, 512.

Reid, M. J., and Moran, J. M. 1981, *Ann. Rev. Astr. Ap.*, in press.

Sargent, A. I., van Duinen, R. J., Fridlund, C. V. M., Nordh, H. L., and Aalders, J. W. G. 1981, *Ap. J.*, **249**, 607.

Schwartz, P. R., and Buhl, D. 1975, *Ap. J. (Letters)*, **201**, L27.

Scoville, N. Z., Hall, D. N. B., Kleinmann, S. G., and Ridgway, S. T. 1981, *Ap. J.*, **253**, in press.

Simon, T., and Joyce, R. R. 1981, in preparation.

Solomon, P. M., Huguenin, G. R., and Scoville, N. Z. 1981, *Ap. J. (Letters)*, **245**, L19.

Strom, K. M., Strom, S. E., and Vrba, F. J. 1976, *A.J.*, **81**, 308.

Tucker, K. D., Kutner, M. L., and Thaddeus, P. 1973, *Ap. J. (Letters)*, **186**, L13.

Welch, W. J., Wright, M. C. H., Plambeck, R. L., Bieging, J. H., and Baud, B. 1981, *Ap. J. (Letters)*, **245**, L87.

White, G. J., and Phillips, J. P. 1981, *M.N.R.A.S.*, **194**, 947.

Zuckerman, B. 1981, *IAU Symposium 96, Infrared Astronomy*, ed. C. G. Wynn-Williams and D. B. Cruikshank (Dordrecht: Reidel), p. 275.

Zuckerman, B., Kuiper, T. B. H., and Rodriquez-Kuiper, E. N. 1976, *Ap. J. (Letters)*, **209**, L137.

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