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HIGH SPECTRAL RESOLUTION OBSERVATIONS OF FLUORESCENT MOLECULAR HYDROGEN IN MOLECULAR CLOUDS

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ABSTRACT

The 1–0 S(1) line of molecular hydrogen has been observed at high spectral resolution (16 km s^{-1} FWHM) in several sources where the emission was suspected of being fluorescent. In NGC 2023, the Orion Bar and Parsamyan 18 the *S*(1) line is unresolved, and the line center close to the rest velocity of the ambient molecular cloud. Such behavior is expected for UV-excited line emission. The H_2 line widths in molecular clouds thus can serve as a diagnostic for shocked and UV-excitation mechanisms; if the lines are broader than several km s^{-1} or velocity shifts are observed across a source it is likely that shocks are responsible for the excitation of the gas.

Subject headings: infrared: spectra — interstellar: molecules — molecular processes — nebulae: Orion nebula.

I. INTRODUCTION

The fluorescence of molecular hydrogen (H_2) gas in the interstellar medium is now a firm observational phenomenon (e.g., Gatley *et al.* 1987). In this process infrared line emission from H_2 follows the absorption of a UV photon by the molecule, raising it to an excited electronic state, and subsequent decay to an excited vibrational level of the ground electronic state (e.g., Black and Dalgarno 1976). The fluorescence is the radiative decay, via infrared vibration-rotation transitions, down the vibrational ladder. It has been a matter of common practice to distinguish between fluorescent and shock-excited H_2 emission by comparing intensities of lines from several vibrational levels. In low-density gas ($\leq 10^4$ cm^{-3}), fluorescence is characterized by strong emission lines from excited vibrational levels, with, in particular, 1–0 *S*(1)/2–1 *S*(1) line ratio of ~2 (e.g., Black and Dalgarno 1976; Hollenbach and Shull 1977; Black and van Dishoeck 1987). The observed spectra in the reflection nebulae NGC 2023 (Gatley *et al.* 1987) and Hubble 12 (Dinerstein *et al.* 1988) are characteristic of fluorescent emission. In contrast, shock-excited spectra, in which the H_2 levels are collisionally excited, are dominated by emission lines from the $v = 0$ and 1 levels, with, in particular a 1–0 *S*(1)/2–1 *S*(1) line ratio of ~10 (e.g., Kwan 1977; London, McCray, and Chu 1977; Shull and Hollenbach 1978; Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982). Shock-excited emission has been observed in many sources, most notably the star-forming region OMC 1 (e.g., Gautier *et al.* 1976; Beckwith *et al.* 1978; Scoville *et al.* 1982; Brand *et al.* 1988).

Recent theoretical work has shown that discriminating between the two exciting mechanisms on the basis of line intensities (in particular, by using the ratio of the 1–0 *S*(1) and 2–1 *S*(1) lines) is not straightforward in all cases. In a photodissociation region (PDR) (e.g., a molecular cloud illuminated by UV radiation; see Tielens and Hollenbach 1985*a*) which is sufficiently dense ($\geq 10^5$ cm^{-3}), collisional de-excitation of radiatively populated levels can move the level populations toward a thermal distribution and give the spectrum the appearance of shocked emission (Sternberg and Dalgarno 1989; Burton, Hollenbach and Tielens 1989*b*). In addition, it is possible that emission from certain kinds of shocks may appear "fluorescent." If the shock speed is sufficiently fast ($\geq$40 km s^{-1}) to dissociate all of the H_2, which then reforms on the surfaces of dust grains in cooler downstream regions, and is subsequently ejected, a "reformation" spectrum will result. The details of this process are somewhat uncertain, but Hollenbach and McKee (1989) suggest that highly excited vibrational lines may result, similar to those produced in the UV-excited radiative cascade.

Several recent observations of H_2 emission line spectra show characteristics of both emission processes. In the Orion Bar, an ionization front (IF) associated with the Trapezium stars, Hayashi *et al.* (1985) found that the ratio of the 1–0 and 2–1 *S*(1) lines varies from unity to ~10, the latter value occurring just behind the IF. The authors speculate that radiative excitation is occurring everywhere, but that just behind the IF a shocked layer exists, the shock wave being driven by the expansion of the H II region. However, it is hard to drive such a shock wave faster than ~3 km s^{-1} (Hill and Hollenbach 1978), which is too slow to significantly excite the vibrational levels of H_2. A plot of energy level against column density shows the lower level lines having apparent excitation temperatures of ~2000 K, typical of "shocks," while ratios of higher level lines are typical of "fluorescence" (Hippelein and Münch 1989). Tanaka *et al.* (1989) find that both radiative and thermal contributions are required to explain the excitation temperatures measured in some planetary nebulae, H II regions and reflection nebulae. In other planetary nebulae (e.g., the Dumbbell, the Ring, and NGC 6720; Zuckerman and Gatley 1988), the H_2 appears to be shock-excited on the evidence of line ratios. However, there appear to be no plausible forces available to drive a shock in order to match the intensity of the H_2 line emission (unless the collision rate coefficients have been severely underestimated and/or H-H_2 collisions dominate over H_2-H_2); yet there is an abundance of UV photons available for pumping the molecules.

In molecular clouds there is another way to distinguish between shock-excited and fluorescent line emission, through the velocity dispersion of the excited gas. Shocks are associated with bulk motions and high velocities. Velocity widths are observed to be large in shocks, occasionally greater than 100 km s^{-1} (e.g., as in the bipolar outflows OMC 1 [Nadeau and Geballe 1979; Scoville *et al.* 1982] and DR 21 (Garden *et al.* 1986), and the supernova remnant IC 443 [Burton 1987]. Even in shocked sources where the lines are currently unresolved, such as the bipolar outflow NGC 2071, evidence for motions may be seen by comparing the emission velocities at different locations (Burton *et al.* 1989*a*). In contrast, fluorescent emission should occur at the ambient cloud velocity and the line width should be just the thermal or turbulent velocity dispersion of the cloud. This is less than 3 km s^{-1} and thus unresolvable with current observing techniques.

We have therefore conducted a program to measure the velocity profiles of H_2 lines in several fluorescent, or suspected fluorescent sources. We have observed the profiles at high spectral resolution, although the low surface brightness of the line emission necessitated the use of a large aperture, which in turn somewhat degraded the resolution. In this paper we show that the H_2 lines in most or all of the sources observed are quite narrow, a result consistent with their line emission being due to fluorescence.

II. OBSERVATIONS

The profiles of the H_2 1–0 *S*(1) (2.1212544 μm) line in the sources listed in Table 1 were measured at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii, on 1988 January 20 and 21, utilizing a scanning Fabry-Perot interferometer (FP) in series with a circular variable filter (CVF) with resolving power 120, tuned to transmit at 2.12 μm. The aperture diameter was 8″ FWHM, which degraded the resolution of the FP from 12 km s^{-1} (its value in parallel light) to $\sim$16 km s^{-1}. Spatial chopping and nodding were performed, with a throw of 120″ E-W. Other details of the observations are listed in Table 1. The FP was scanned over ranges of 60–85 km s^{-1}, in steps of 5 km s^{-1}. Adjacent orders of the FP are separated by 450 km s^{-1}, thus five orders of the FP are included within the FWHM of the CVF. We are aware of four lines which may possibly contaminate the 1–0 *S*(1) profiles. The 3–2 *S*(4) line, two orders away at 2.1274 μm, lies -28 km s^{-1} from the line center of the 1–0 *S*(1) line, and the 8–6 O(4) line at 2.1210 μm lies at -36 km s^{-1}. The 7–5 O(6) line, at 2.1084 μm, four orders away, and thus significantly attenuated, lies at -39 km s^{-1} (all wavelengths in standard air, from Black and van Dishoeck 1987 and Bragg, Brault, and Smith 1982). We estimate that in a shocked source the contamination by each line will be less than 1% of the 1–0 *S*(1) line (Brand *et al.* 1988), but that in a (low-density) fluorescent source the contamination will be (not including attenuation) $\sim$6%, 7%, and 3%, respectively (Black and van Dishoeck 1987). The He I 3^3P–4^3S multiplet, with weighted mean wavelength 2.112022 μm (Litzén 1970), will occur at $+31$ km s^{-1} if it is emitted in the same source as the 1–0 *S*(1) line and at the same local velocity. (N.B. The uncertainty in the last figure of these wavelengths results in a ± 3 km s^{-1} error in the velocity shifts above.)

TABLE 1

OBSERVING LOG

Object	(0, 0) Position	Integration Time per Point	Number of Spectral Points
Orion Bar .... θ_2 Ori A	$5^h32^m55^s.4$ − 5°26′50″.7	40	13
OMC 2 .... IRS 4−S	5 32 59.8 − 5 11 30.1	35	18
NGC 2023 .... HD 37903	5 39 07.3 − 2 16 58	50	15
Parsamyan 18 ...... Star A	6 57 16.6 − 7 42 16	60	17
OMC 1 .... Peak 2	5 32 48.2 − 5 24 30	4	43

The *S*(1) profiles are shown in Figure 1, together with the profile of an argon lamp line (19 km s^{-1} FWHM; the Ar profile is pressure broadened from the 16 km s^{-1} FWHM of the instrument) at 2.1338708 μm (in vacuo; Norlén 1973). The peak emission velocities have been shifted to 0 km s^{-1} and the fluxes normalized to unity. Details are given in Table 2. Velocities of line centers were measured relative to OMC 1 Peak 2, and are estimated to be correct to ± 3 km s^{-1}. Drifting of the FP plates was monitored by periodically measuring the frequency of maximum line emission at peak 2; the drift over the course of a night was steady and totaled 5 km s^{-1}, and thus was negligible for any single observation. Line fluxes are given relative to peak 2.

III. RESULTS

In Figure 1 it can be seen that the 1–0 *S*(1) line at OMC 1 Peak 2 is resolved, with an observed FWHM 37 km s^{-1} (consistent with Nadeau and Geballe 1979). For the Orion Bar, NGC 2023, and Parsamyan 18, the *S*(1) line is essentially unresolved with FWHMs ranging from 16 to 20 km s^{-1}. The *S*(1) line in OMC 2 is somewhat broader. There are features at about the 10% level of the peak flux at ~ -30 km s^{-1} in several of the profiles, which may be due to higher excitation lines coming through other orders of the FP (see § II). For Parsamyan 18 8 W there is a feature at $\sim +35$ km s^{-1}, which may be due to the He I 3^3P–A^3S triplet; this feature is not seen in any other sources. For the the Orion Bar, OMC 2, NGC 2023 and Parsamyan 18 the *S*(1) line emission velocity is, within the errors, at the velocity of the ambient molecular cloud determined by CO line observations (see Table 2).

IV. DISCUSSION

The observed narrow line profiles are centered at the rest velocity of the respective ambient molecular clouds, which is as expected for UV-excited line emission. However, such profiles could be produced by a single shock moving perpendicular to the line of sight. Thus these data are in themselves insufficient to demonstrate that the emission is fluorescent. Therefore, in the rest of this section we discuss additional evidence for fluorescence in the four sources that are observed.

NGC 2023.—The reflection nebula NGC 2023, excited by a B1.5 star HD 37903, is the source where the first clear identification of fluorescent H_2 line emission was made (Gatley *et al.* 1987; Black and van Dishoeck 1987). Many other observed phenomena are best interpreted as occurring on the surface of the molecular cloud as a result of UV irradiation (e.g., Pankonin and Walmsley 1976, Crawford *et al.* 1985; Witt and Schild 1988; Burton *et al.* 1989*c*) and have a close spatial coincidence with the H_2 line emission. Thus the evidence for H_2 fluorescence is particularly convincing in NGC 2023.

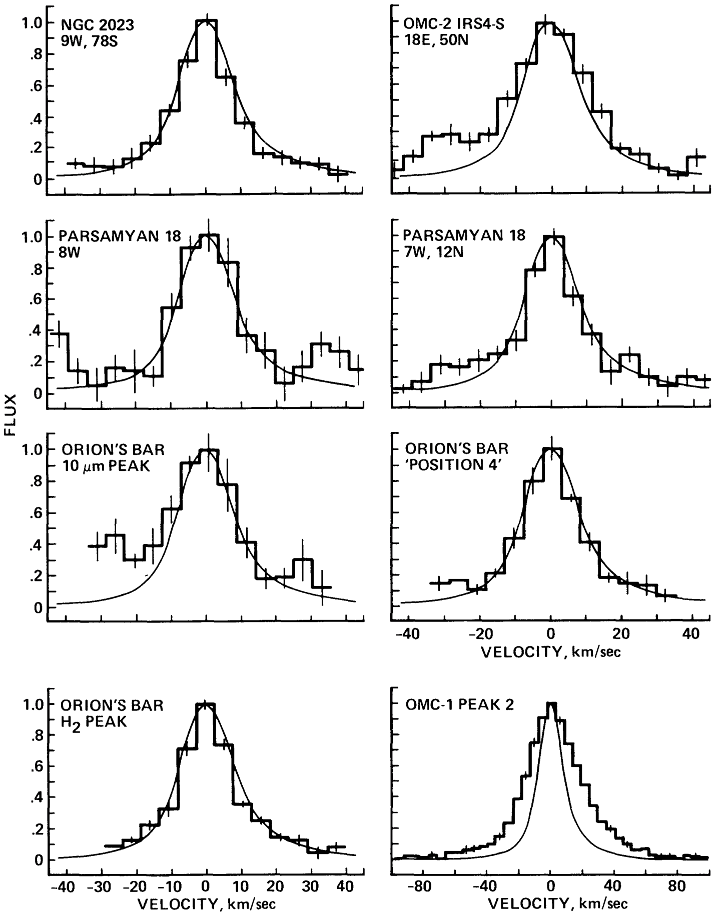

FIG. 1.—The observed profiles of the H_2 1–0 $S(1)$ line, at 2.1218 μm, in the sources NGC 2023, OMC 2, Parsamyan 18, the Orion Bar, and, for reference, in the shock-excited source OMC 1. An argon lamp line is shown for each profile. All profiles have been normalized to unit flux and have had their central velocity set to 0 km s^{-1}. Relative fluxes, FWHMs and V_{LSR} emission velocities are given in Table 2.

TABLE 2

SOURCE PARAMETERS

Source	Offset (″)	Observed FWHM of Line (km s^{-1})	Velocity of 1–0 S(1) Line (km s^{-1})	Velocity of Ambient Cloud (km s^{-1})	Relative Flux
Orion Bar	38.5 W 9.3 S (10 μm peak)[a]	20	+14.5	+11[b]	0.0095
	30 W 18 S (Position 4)[b]	17	+14		0.029
	45 W 25 S (H_2 peak)	17	+11.5		0.046
OMC 2	18 E 50 N (H_2 peak)	23	+13	+10.5[c]	0.030
NGC 2023	78 S 9 W (H_2 peak)	17	+11	+11[d]	0.031
Parsamyan 18	8 W	19	+15.5	+13.4[e]	0.011
	7 W 12 N	16	+15.5		0.015
OMC 1 Peak 2	0 E 0 N	37	+13	+9	1.0

[a] Becklin *et al.* 1976.

[b] Hayashi *et al.* 1985.

[c] Fischer *et al.* 1985.

[d] Gatley *et al.* 1987.

[e] D. Wooden and M. Cohen (private communication).

[f] An approximate line flux for OMC 1 Peak 2 is 4×10^{-19} W cm^{-2} through an 8″ aperture (Beck and Beckwith 1983). All velocities are with respect to the local standard of rest. H_2 velocities are estimated to be accurate to ± 3 km s^{-1}. They are measured relative to the line center at Peak 2, for which the values given are from Nadeau and Geballe 1979.

Parsamyan 18.—The reflection nebula P 18 has a 1–0/2–1 S(1) line ratio of 1.7, as expected for fluorescent line emission (Sellgren 1986). The UV-excited infrared emission bands at 3.3 μm (Gatley *et al.* 1987), 6.2, 7.7 μm, and 11.3 μm (Cohen *et al.* 1986), have been observed. The H_2 1–0 *S*(1) line and the 3.3 μm emission feature are morphologically similar (Burton *et al.* 1989*c*). Thus, the observed narrow H_2 line profile is entirely consistent with the previous understanding of the excitation of the H_2.

The Orion Bar.—From the variation of the 1–0/2–1 *S*(1) line ratio across the ionization front in the Orion Bar, Hayashi *et al.* (1985) concluded that both UV-excitation from the Trapezium stars, and shock-excitation driven by the expansion of the H II region were responsible for the H_2 line emission. As pointed out earlier, however, it is difficult to drive such a shock wave sufficiently fast to excite the vibrational H_2 lines. In addition, the H_2 line emission peaks 15″ away from the ionization front, whereas it would be expected to occur immediately adjacent to the front if the H_2 were shock-excited. A detailed model of the region by Tielens and Hollenbach (1985*b*) fits the observed [O I] 63 μm and 146 μm, [C I] 609 μm, [C II] 158 μm and low-lying CO rotational lines by a PDR model with density 2×10^5 cm^{-3} and a UV-field appropriate to that measured for the Trapezium stars. The high-excitation H_2 lines observed by Hippelein and Münch (1989) require a density of $\sim 10^6$ cm^{-3} in the same UV-field for this model (Burton *et al.* 1989*b*), but a possible underestimation of H_2 collisional de-excitation rates may lower this density to a value closer to that determined from the fine-structure lines. The 3.3 μm emission feature also originates in a neutral region behind the ionization front (Sellgren 1981; Aitken *et al.* 1979). However, images of the 3.3 μm feature and the *S*(1) line are not identical, with the *S*(1) line peaking a further 10″ away from the ionization front than the 3.3 μm feature (Burton *et al.* 1989*c*). The strongest *S*(1) emission occurs in the region assigned as shock-excited by Hayashi *et al.* (1985). Emission from the 3.3 μm feature does arise here too, although its intensity is reduced relative to that closer to the ionization front.

On the basis of these data and the current H_2 spectra, we cannot rule out the possibility that some of the H_2 line emission from the Orion Bar is shock-excited, although it seems clear from the narrow line widths that the bulk of the emission is fluorescent. It appears likely that much of the H_2 line emitting gas is sufficiently dense ($> 10^5$–10^6 cm^{-3}) that collisions thermalize the vibrational levels of the H_2 molecules before they can radiate. The emission spectrum therefore appears similar to that expected from hot, shocked gas, and the lines are narrow and emitted at the rest velocity of the cloud, as observed.

OMC 2.—H_2 line emission in OMC 2 is centered on IRS4, (Fischer, Righini-Cohen, and Simon 1980; Thronson and Thompson 1982) and extends ∼90″ NNE as a narrow "jet" (Burton, Garden, and Russell 1990). The present observations were centered on a bright clump situated about half way along the "jet." No infrared sources have been observed in the region of this "jet." On the basis of a 1–0/2–1 *S*(1) line ratio of 7 for the emission on IRS 4, Thronson and Thompson (1982) argue for shock-excitation of the gas. The noise level on their 2–1 *S*(1) line is high, however, so the interpretation is subject to some doubt. ^{12}CO line emission is seen with wings extending to ± 6 km s^{-1} away from line center around IRS 4 (Fischer *et al.* 1985). The emission is slightly bipolar, with axis extending NNE from IRS 4 and centered at about (10 E, 20 N) from the source; i.e., in a direction similar to the "jet" seen in the *S*(1) line. IRS 4-N is the most luminous member of the star cluster making up OMC 2 and appears to be surrounded by a disk oriented E-W (Pendleton *et al.* 1986; Rayner *et al.* 1989). This disk may collimate an outflow from IRS 4-N. Thus, on this evidence, it seems plausible to assume that the *S*(1) line emission from OMC 2 is shocked. However, the line profile observed is narrow (although somewhat broader than one would expect from a quiescent cloud), and the emission velocity is close to the rest velocity of the cloud. These are indicative of fluorescence, but could also be consistent with a low-velocity shock, or a faster one traveling in the plane of the sky. The observed CO velocities are also too small to significantly populate the vibrational H_2 levels if there are shocks moving with the same velocities. However, examples are known (e.g., DR 21; Garden *et al.* 1986) where observed H_2 velocities far exceed those observed in CO. Further observations of the H_2 line emission, in particular spectra and profiles taken at several positions along the "jet," are required in order to determine the source of excitation.

V. CONCLUSIONS

We have measured the profile of the H_2 1–0 *S*(1) line at high resolution in several sources where the emission is suspected of being fluorescent. In each case we find that the line is narrow and the emission velocity is close to that of the ambient cloud. This is as expected in sources excited by UV-radiation, but is not commonly observed in shock-excited sources. Thus in some cases high-resolution spectroscopy can provide an additional diagnostic for distinguishing between shocks and fluorescence. Taken together with other evidence, it is clear that the H_2 line emission in NGC 2023, Parsamyan 18, and the Orion Bar result from fluorescence. In OMC 2 we cannot distinguish yet between shocks and fluorescence.

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