INFRARED OBSERVATIONS OF INTERSTELLAR MOLECULAR HYDROGEN

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1. INTRODUCTION

Emission from vibrationally excited molecular hydrogen has been detected from a wide range of astronomical targets during the last decade (e.g. Shull and Beckwith 1982). In all cases the H_2 has been shock excited, and we have grown accustomed to the idea that H_2 is a useful tracer of interstellar shocks.

Yet the hydrogen molecule can also be excited by ultraviolet radiation (Gould and Harwit 1963; Black and Dalgarno 1976; Shull 1978; Black and van Dishoeck 1987), and the first searches for H_2 emission were based on predictions of fluorescent line emission (Werner and Harwit 1968; Gull and Harwit 1971).

Theory predicts that fluorescent H_2 should occur widely in the interstellar medium. A major result of this paper is to report that this prediction is correct. The failure of early experiments to detect fluorescence is directly attributable to a lack of sensitivity to diffuse emission.

An instrument with a large beamsize (20 arcseconds) which employs a frequency-switching Fabry-Perot interferometer (rather than the conventional infrared technique of sky chopping) has been used at UKIRT to measure diffuse H_2 emission. Fluorescent emission and shocked emission are now both observed over large areas, and useful images in H_2 can be constructed. Results are presented for the reflection nebula NGC 2023, planetary nebulae, HII regions, and the Galactic center.

In several cases the infrared H_2 images bear a striking resemblance to radio molecular images, obtained at the same spatial resolution using the Nobeyama 45 meter telescope; in such cases the high velocity resolution available at radio frequencies gives detailed information about the dynamics of the excited molecular gas.

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2. FLUORESCENT GAS IN REFLECTION NEBULAE

The theory of fluorescent excitation of H_2 predicts that strong H_2 emission will be observed when an early type star irradiates the boundary of a dense molecular cloud. The well-known reflection nebula NGC 2023 is therefore an obvious target in which to search, for Sellgren (1984) has discovered in this nebula a bright near infrared continuum attributable to thermal emission from tiny grains, briefly heated to ~1000°K by absorption of individual ultraviolet photons.

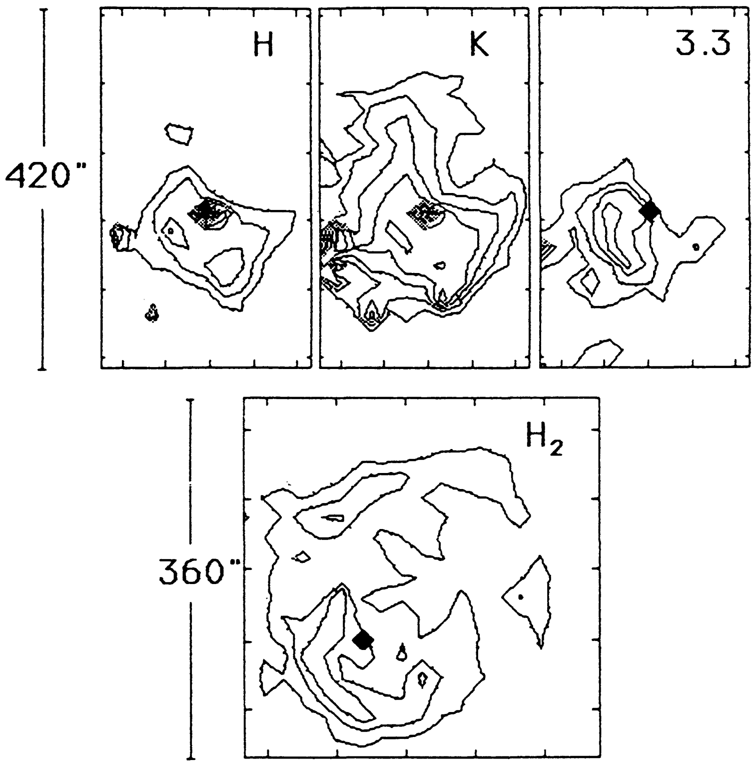

Figure 1

Figure 1 shows maps of NGC 2023 at H(1.65μm), K(2.2μm), in the "unidentified" 3.3μm dust feature and in the v = 1-0 S(1) line of H_2. The maps at H and K are identically normalised relative to the central star, and directly confirm Sellgren's result; the extended emission is much more conspicuous at K.

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The H_2 emission comes from a shell around Sellgren's infrared nebula; the molecular hydrogen may be dissociated nearer the exciting star. The molecular hydrogen map appears similar to that of the 3.3μm dust feature; this ubiquitous dust feature is also believed to be of fluorescent origin, produced when small grains or large molecules, polycyclic aromatic hydrocarbons, are irradiated by ultraviolet light (Leger and Puget 1984; Sellgren et al. 1985).

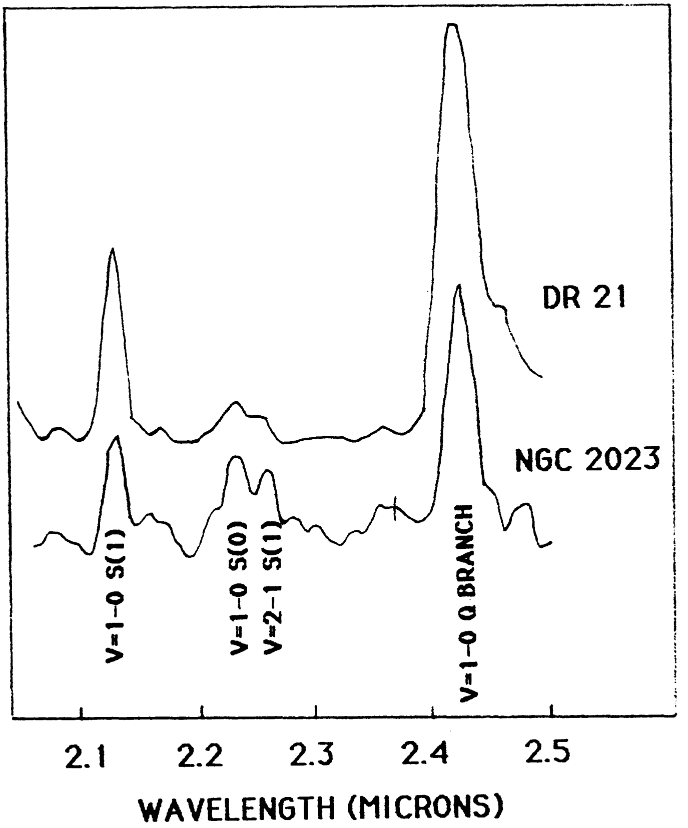

Figure 2

Figure 2 compares K band spectra of DR21, a typical shocked H_2 source (Garden et al. 1986), and NGC 2023. In DR21 both the vibration and rotation temperature of the emitting gas are of order 2000°K. The striking difference between the spectra is that the v = 1-0 S(0) and v = 2-1 S(1) lines are much more prominent in NGC 2023. Of course the ratio v = 2-1 S(1) to v = 1-0 S(1) measures the vibration temperature and the ratio v = 1-0 S(0) to v = 1-0 S(1) measures the rotation temperature.

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By direct comparison with DR21 we can see immediately that, in NGC 2023, the vibration temperature of the H_2 is much higher than 2000K, and the rotation temperature is much lower. This is fluorescence; ultraviolet excitation followed by radiative decay populates the vibrational levels of H_2 without populating the rotational levels of the originally cold gas.

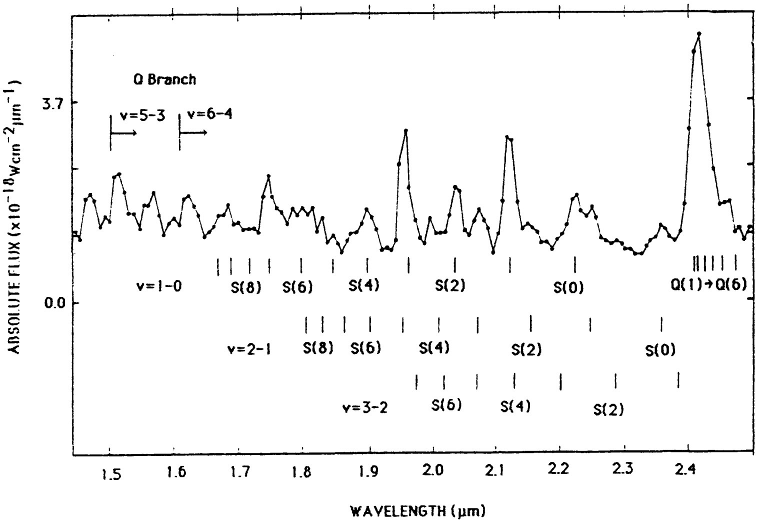

Figure 3

Figure 3 presents a more detailed spectrum of NGC 2023, measured 80 arcseconds south of the exciting star. The richness of this spectrum, and the presence of lines from highly excited vibrational states, confirms that the excitation is by fluorescence. The agreement between observed and predicted line ratios is excellent (Black and van Dishoeck 1987). Sellgren (1986) has confirmed the detection of fluorescent H_2 in NGC 2023, and has discovered fluorescence in another reflection nebula.

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3. PLANETARY NEBULAE

Shocked H_2 emission is observed from planetary nebulae, and maps in H_2 are important in understanding PN morphology. No planetary nebula, not even NGC 7027 (Beckwith et al. 1980), has previously been completely mapped in H_2.

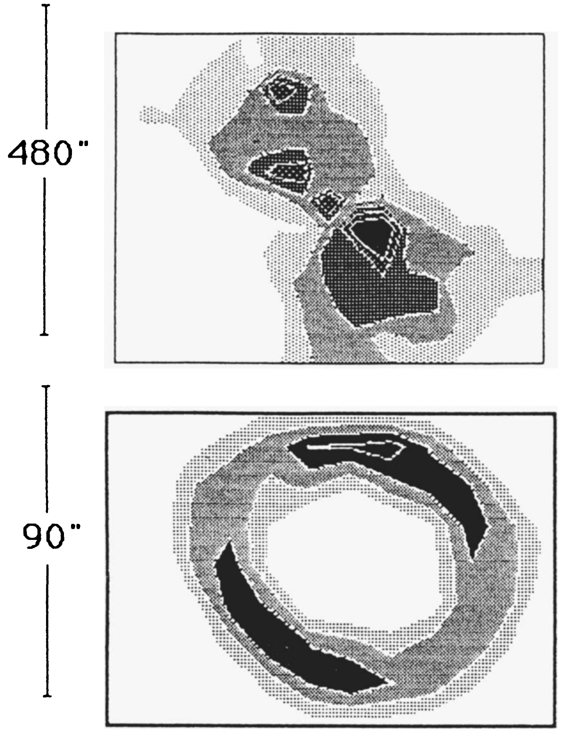

Figure 4

Figure 4 shows images of the Ring Nebula and the Dumbbell Nebula in the v = 1-0 S(1) line of H_2 (Zuckerman and Gatley, unpublished). These large images are good illustrations of the power of the wide field mapping approach; a map of a portion of the Ring Nebula has been presented by Beckwith, Persson and Gatley (1978). The Ring appears larger in H_2 than in visible light, indicating that the H_2 emission comes from outside the ionised gas.

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4. HII REGIONS

4.1. DR21

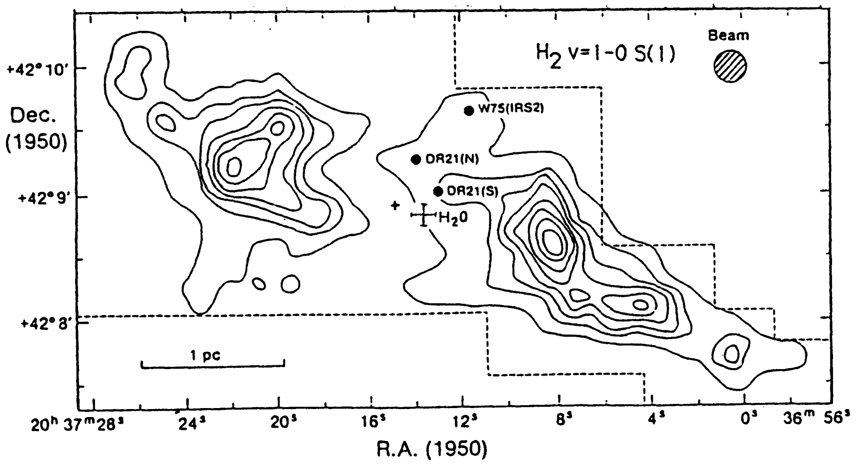

Figure 5

Figure 5 shows a map of the DR21 region in the v = 1-0 S(1) line of H_2; a highly collimated, bipolar molecular jet is present, in which the gas is shocked (Garden et al. 1986). The jet is centered on the DR21 HII region/molecular cloud core; the positions of other sources in the field are indicated. This is probably the most luminous and largest galactic H_2 source presently known.

4.2. M17

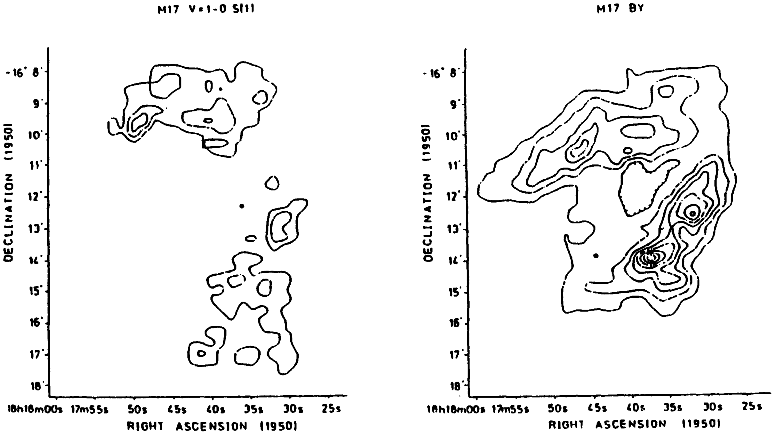

Figure 6

Figure 6 shows maps of M17 in the Brackett gamma line of HI, and in the v = 1-0 S(1) line of H_2. The Bγ map shows the distribution of the ionised gas, and is, of course, similar in appearance to radio continuum maps of the plasma (e.g. Felli et al. 1984); the envelope of the map by Felli et al. is indicated below in Figure 7 for comparison. The H_2 emission is located at the interface between the HII region and the molecular cloud.

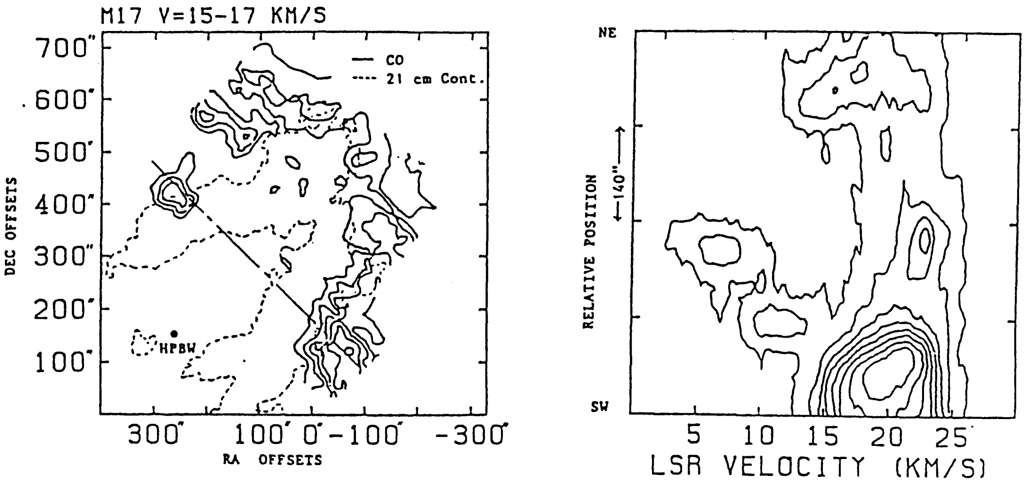

Figure 7

Figure 7a shows a velocity channel map in ^{12}CO at a velocity which is blueshifted by several km/sec from that of the quiescent molecular cloud; the location of the HII region is indicated by a contour from the 21cm map of Felli et al. (1984).

The CO emission, like the H_2, arises from clumps at the interface with the HII region. Conspicuous clumps in the northeast and southwest of the H_2 map are also bright in CO at this velocity. To display the global velocity structure of the nebula in more detail Figure 7b shows a position-velocity diagram along the NE-SW line indicated in Figure 7a; position-velocity diagrams (not shown here) along nearby parallel lines look very similar.

This is a very striking demonstration of the existence of an expanding shell of molecular material driven by the HII region. The shell is broken along the northern bar of the HII region, in good agreement with the "blister" model description (Icke, Gatley and Israel 1979), and more simply, with the fact that this part of the nebula is seen with relatively little optical obscuration — which is consistent with the inclusion of this nebula in the Messier list.

CO emission is seen over a velocity range of ~20 km/sec, and so the expansion of the HII region can in principle produce appreciable shocked H_2 emission. Copious amounts of ultraviolet light capable of causing fluorescence also penetrate the H_2 emitting region in M17. It will be straightforward to determine the excitation mechanism for the H_2 by measuring line ratios, but this measurement has not been performed yet for M17. Comparison with the results on the Orion Bright Bar, presented below, illustrates the method.

4.3. The Orion Nebula

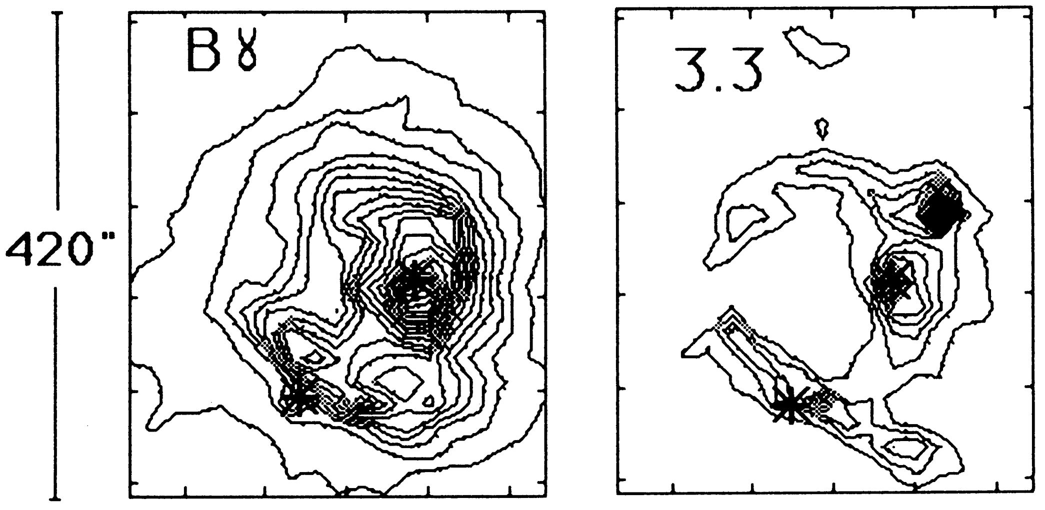

Figure 8

Figure 8 compares the appearance of the Orion nebula in ionised gas (Brackett γ) and hot dust (the 3.3μm "unidentified" feature). The positions of the stars θ^1C Ori and θ^2A Ori are shown in each frame. The dust feature traces the locus of the interface between the HII region and the neutral cloud; it is bright on every edge of the nebula except for the east.

Figure 9 shows an overlay of a map of the Orion Nebula in the v = 1-0 S(1) line of H_2 (as contours) on a map of integrated ^{12}CO (as grey scale). The similarity of the H_2 and CO images is very striking. The molecular emission clearly arises from the interface between the HII region and the neutral cloud as in the case of M17.

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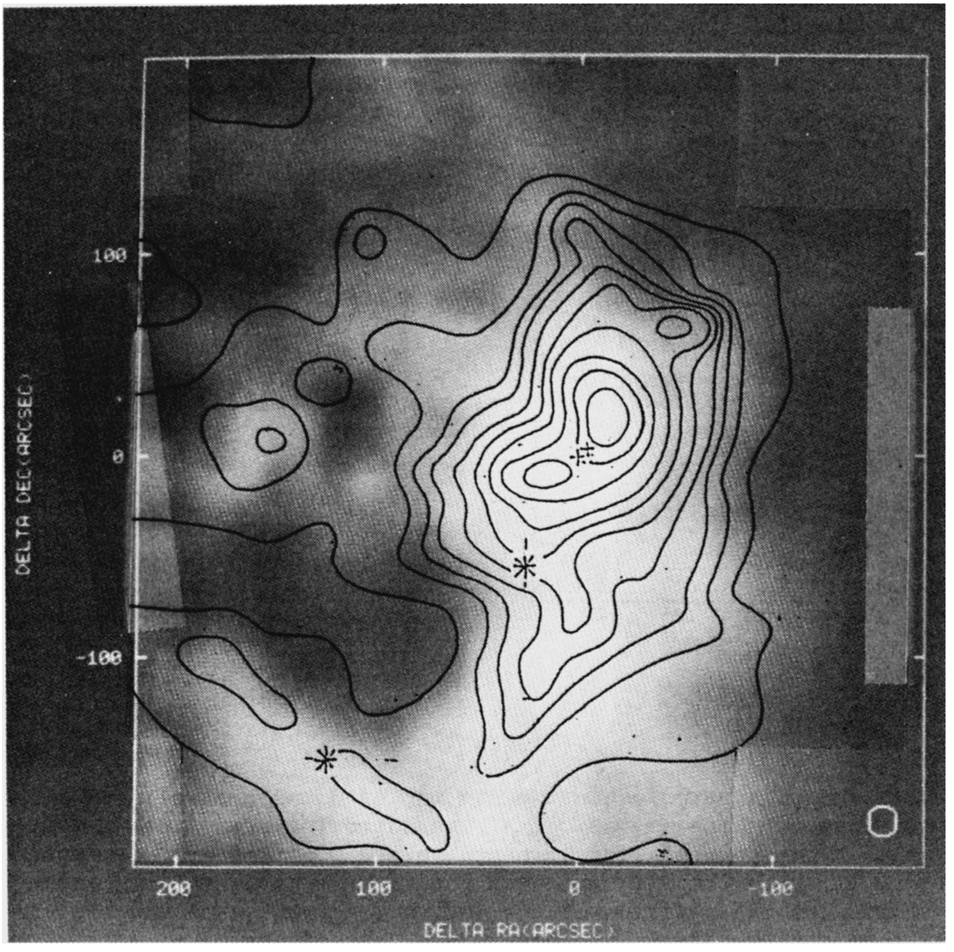

Figure 9

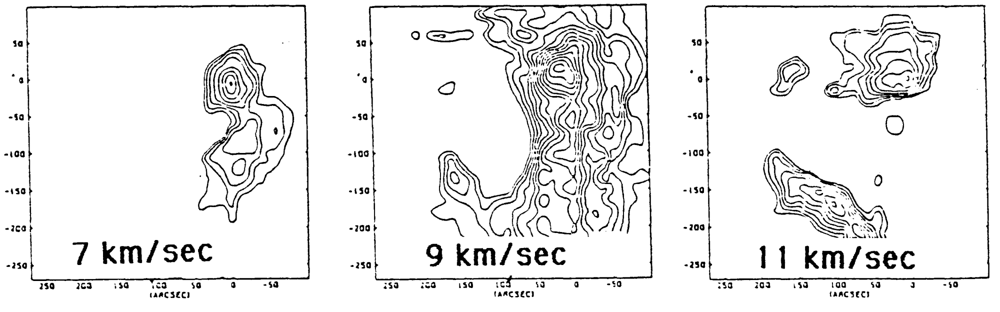

Figure 10

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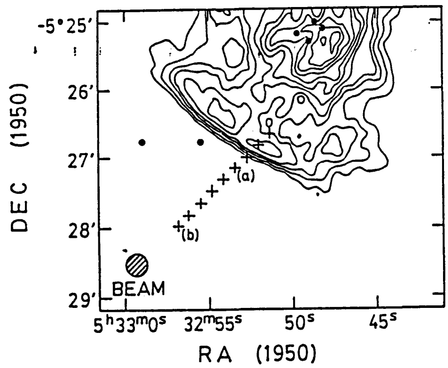
Figure 10 compares the CO emission at the quiescent cloud velocity (9 km/sec) with that at slightly blueshifted and redshifted velocities (7 and 11 km/sec). The differences between these maps are large, and, as in M17, distinct kinematic behaviour (presumably expansion) is associated with the interface layer between the HII region and the neutral cloud. The southeastern edge of the Orion nebula, the so-called "Bright Bar," provides an excellent laboratory in which to study the interface layer in more detail.



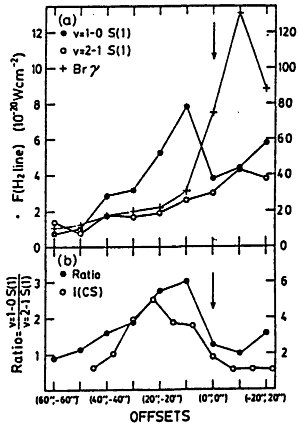


Figure 11

Figure 11 shows, superposed on the 6cm map of Johnson et al. (1983), the positions at which Hayashi et al. measured infrared line strengths. The plots of line strength versus position are displayed in Figure 11, with the HII region at the right side of the plot; the arrow indicates the position of the ionisation front, and the profile of Brγ line strength falls steeply to the left of the plot, as expected.

Both the v = 1-0 S(1) line and the v = 2-1 S(1) line are detected at every position; their ratio is a measure of the vibration temperature (section 2). The v = 1-0 S(1) line shows a sharp peak in intensity just outside the ionisation front, but the v = 2-1 S(1) line does not. The line ratio therefore changes abruptly just outside the ionisation front. Elsewhere, as shown in Figure 11, the numerical value of the line ratio is near unity, indicative of fluorescent H_2. Just outside the ionisation front, where the line ratio rises, the gas is shocked; the spatial distribution of the shocked gas can be seen, parallel to the ionisation front, in the molecular maps of Figures 9 and 10. The line ratio is compared with the intensity of the CS emission in Figure 11; the CS is believed to arise in a shock compressed layer (Omodaka et al. 1984). This compressed layer is also seen distinctly in the redshifted CO channel map of Figure 10.

The Orion nebula thus exhibits both fluorescent and shocked molecular hydrogen. Particularly interesting is the absence of bright fluorescent H_2 emission from the sheet of material between the ionisation front and the shock. This sheet is neutral, strongly irradiated by non-ionising ultraviolet radiation, and is viewed at a most favorable, edge-on, aspect; the H_2 must be dissociated (cf Tielens and Hollenbach 1985).

5. THE GALACTIC CENTER

The nucleus of the Milky Way is encircled by a ring of molecular material at a radius of approximately two parsecs (Gatley *et al*. 1984; Genzel *et al*. 1984; Crawford *et al*. 1985). This ring may be both created and excited by the presence of a central nuclear "engine" (Gatley 1984; Gatley *et al*. 1986), and so molecular observations provide useful constraints on the nature of the nuclear source. An interesting feature of the Galactic center molecular ring is that its appearance is somewhat different in different molecular species.

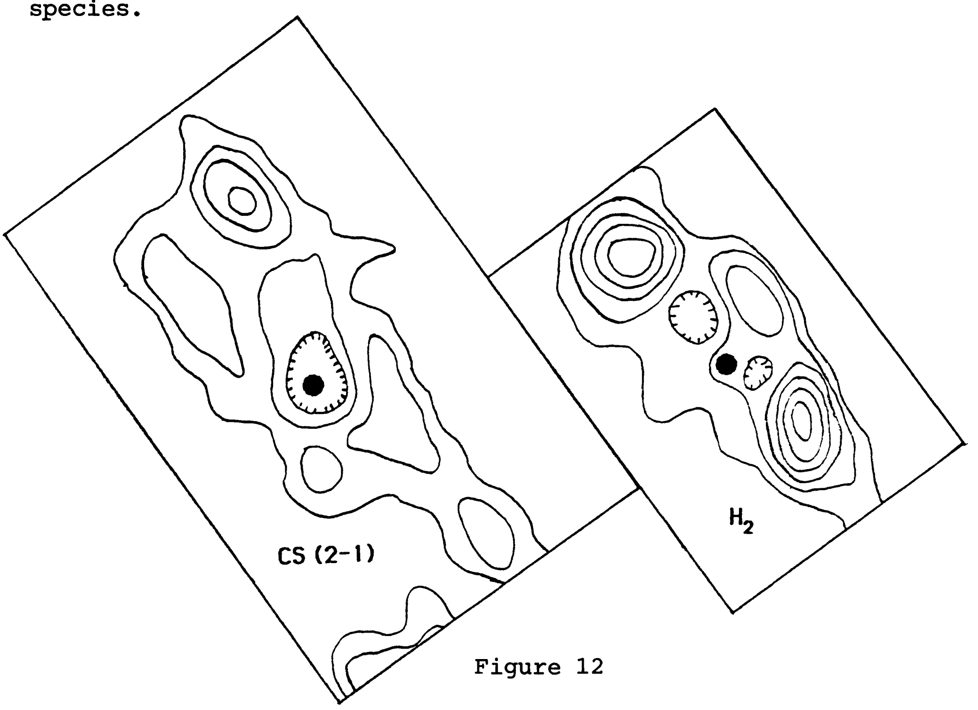


Figure 12

Figure 12 compares maps of the integrated intensity of H_2 v = 1-0 S(1) and CS 2-1. It is worthwhile to bear in mind that excitation changes may occur throughout the molecular ring; in particular both shocks and fluorescence may occur (Gatley *et al*. 1986), for the central object is both a mass-loss object and a bright source of soft ultraviolet radiation.

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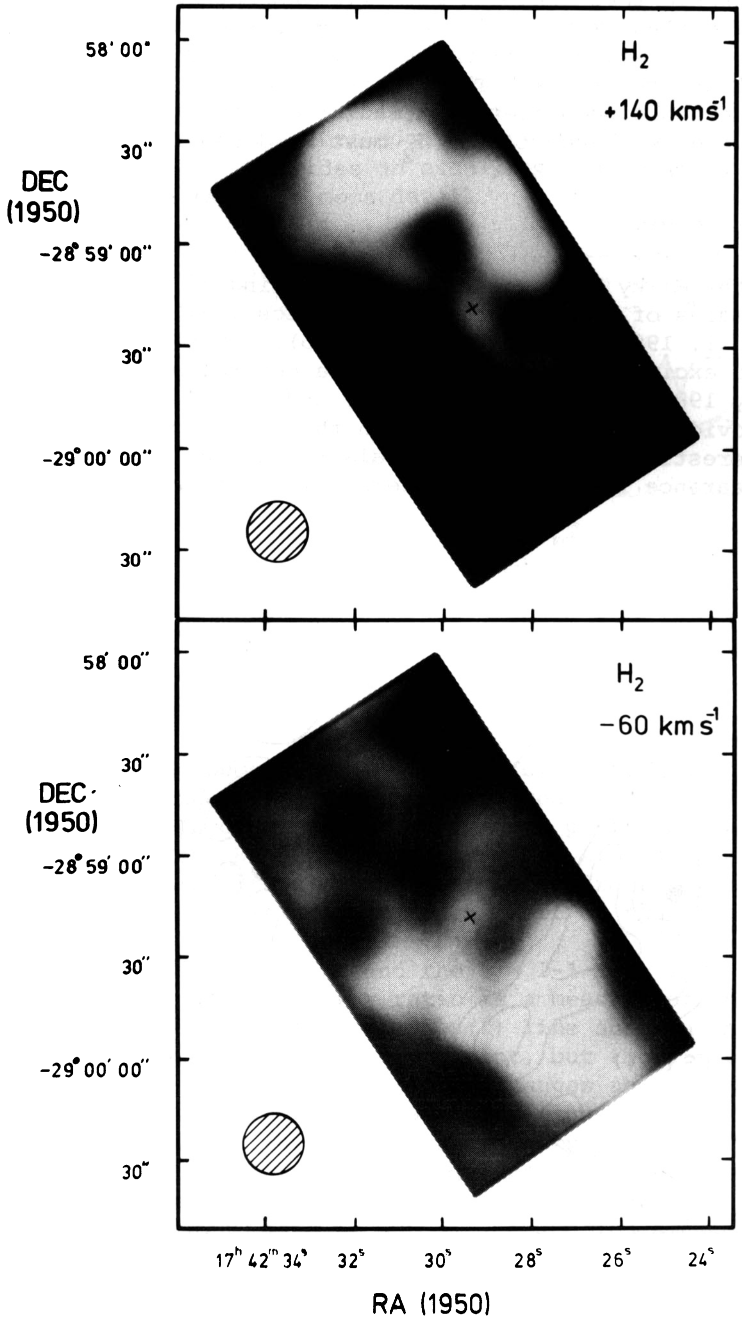

Figure 13

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Figure 13 shows the rotation of the molecular ring, as measured in the v = 1-0 S(1) line of H_2; the velocity resolution is 130 km/sec. The molecular ring is tilted approximately 20° out of the plane of the Galaxy, has a broken and clumpy appearance, rotates at 90 km/sec in the sense of Galactic rotation, and exhibits radial motion (probably infall) at a velocity of 40 km/sec. A plausible model is that the infalling material is ionised by radiation from the central object, forming the infalling plasma streamers which make up the HII region Sgr A (Gatley et al. 1984; Serabyn and Lacy 1985).

It seems increasingly likely that a detailed physical model of the excitation and dynamics of the central few parsecs will be crucial in determining the nature of the nuclear source.

6. CONCLUSIONS

(a) A mapping technique has been developed which is suitable for the study of large sources of H_2 emission, and the method has been applied to a wide variety of astronomical targets.

(b) Spectroscopy of diffuse H_2 emission has led to the discovery of fluorescence.

(c) A collaboration between UKIRT and Nobeyama Radio Observatory has demonstrated the usefulness of comparing molecular line measurements at near infrared and radio wavelengths:

(d) Images of diffuse molecular emission in H_2 and CO are often strikingly similar. In evaluating this result it is important to recall that the vibrational temperature of the emitting H_2 invariably exceeds 1000°K, much higher than that of the CO.

(e) A clumpy expanding molecular shell is often formed as an HII region disrupts its parent molecular cloud.

(f) The structure of the shock compressed layer between an HII region and molecular cloud appears similar in CS and H_2 observations.

(g) The fluorescent excitation of H_2 is a widely observable phenomenon. It will be interesting to determine if fluorescent line emission is an important radiative process for other molecules.

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DISCUSSION

JURA: One way to honour such beautiful observations is to show calculated fluorescent spectra of H_2, with penetration of UV radiation inside the cloud incorporated. The distinction between a thermal spectrum and what one expects from shocks and UV fluorescence is striking. The observed and calculated fluorescence spectra match very well.

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