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High Spectral and Spatial Resolution Observations of the 12.28 µm Emission from H_2 in the Orion Molecular Cloud

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ABSTRACT

The pure rotational S(2) line of molecular hydrogen at 12.28 μm has been looked for in 44 positions in the Orion Molecular Cloud with 6" beams and 35 km s^{-1} spectral resolution; it was detected in 27 positions. Emission has been observed over a velocity range of ±100 km s^{-1}. The lines are approximately symmetric, and have full widths at half maximum ranging from 100 km s^{-1} down to the resolution limit. The distribution of intensities and line shapes is largely consistent with that seen in the 2 μm hydrogen transitions. However, unexpectedly complex line profiles and point-to-point variations in line shapes appear, particularly in the region near IRc9.

I. INTRODUCTION

The pure rotational S(2) line of molecular hydrogen at 12.28 μm, first observed in the Orion Molecular Cloud by Beck, Lacy and Geballe (1979, hereafter Paper I), provides information on a cooler component of gas than that associated with the 2-3 μm vibrational-rotational lines. Since the 12 μm line is much less affected by scattering and obscuration than the 2-3 μm lines, observations with high spatial and spectral resolution should give less ambiguous data on the kinematics of the emitting gas. The observations of Paper I were made from Las Campanas Observatory, Chile. During these observations the atmospheric H_2O lines close to the H_2 line decreased the signal and limited possible conclusions about the line shapes; it was clear that a drier atmosphere was necessary for higher quality data. We report here the results of observations of the 12.28 μm hydrogen emission made at the NASA Infrared Telescope Facility on Mauna Kea, Hawaii, in February and November-December, 1980, and January, 1981. The atmospheric H_2O absorption at 814.51 cm^{-1} was less than 10% deep throughout these observations, as compared to 30-50% deep for the measurements reported in Paper I.

The 12.28 μm S(2) line has now been measured with spatial coverage and spectral resolution comparable to the 2 μm observations of Nadeau and Geballe (1979), Nadeau, Geballe, and Neugebauer (1981, hereafter NGN), and Scoville et al (1981). These more complete observations are described here, with measured spectra displayed and briefly discussed. Detailed comparison of the S(2) line with the 2 μm H_2 and other molecular lines such as CO will be reported later.

II. OBSERVATIONS

The observations were made using the same Fabry-Perot and grating spectrometer described in Paper I with a 6" beam and spectral resolution of 0.10 cm^{-1}, or 35 km s^{-1}. The signal-to-noise ratio did not increase appreciably near the H_2O absorption, and the minimum detectable line intensity (3σ in a resolution element in 45 minutes) was 5×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}. The flux was calibrated from blackbody measurements; systematic and random uncertainties in the flux calibration are estimated to be about ±10%. The wavelength scale was calibrated by reference to an absorption cell of NH_3, giving an uncertainty in the calibration of ±4 km s^{-1}. The rest frequency of the v=0-0, S(2) line was taken to be 814.452±.005 cm^{-1}, as in Paper I.[2]

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[2] Jennings (1981, private communication) has measured the S(2) line in the laboratory to be at 814.4270±.005 cm^{-1}, but he found the NH_3 lines to be shifted as well, so the velocities in Figure 1 would not change if his results were used.

There was evidence for emission in 20 new positions. However, the 12.28 μm line in Orion is quite weak, and several of these cases were weak enough that they need confirmation. Our discussion of the dynamics will be limited to the strongest lines, whose shapes are most accurately determined. The observing procedure was designed to minimize false signals such as varying instrumental offsets. A wobbling secondary mirror was used to chop in a north-south direction between positions separated by 90-120". The spectra were measured in scans lasting 20 seconds and recorded in 256 channels. The spectra were co-added and the sum recorded every 32 scans. The source was switched between signal and reference beams after the 8th and 24th scans to cancel any beam imbalance. After every set of 32 scans the blackbody source and the NH_3 cell were measured to assure that no sudden change had occurred in the system, and after two sets α Ori was observed to check tracking and system stability. Each spectrum presented contains 128 scans or roughly 45 minutes of integration, during which time system performance was checked against four measurements of the blackbody and NH_3 source, and two of α Ori.

Comparison of the Mauna Kea data with those from Chile indicates that the known source of poor signal-to-noise ratios, substantial atmospheric absorption, has been largely removed. From examinations of the subsets of 32 scans it appears that beam imbalance was not affecting the baselines or the apparent noise level; the stronger line shapes reproduce well from observation to observation. Position 1 has been observed three times over a period of 22 months and shows no changes in shape or intensity which would not be attributed to baseline problems or variations in the atmosphere. A potentially large source of error in these spectra is the tracking, which can introduce as much as 2" shift in 10 minutes. For some complex line shapes (section IIb), this may be significant.

Figure 2 shows the 44 positions in Orion where the S(2) line has been looked for. Positions 1-11 were observed from Las Campanas in February-March, 1979, 12-16 from the IRTF on Mauna Kea in February, 1980, 17-32 from the IRTF in November-December, 1980, and 33-44 from the IRTF in January, 1981. In addition, positions 1 and 16 were observed from the IRTF in both February and November, 1980, and position 30 was observed in both November and January.

Figure 1 displays the spectra of the 20 new positions where H_2 was detected. These spectra were divided by an atmospheric transmission function obtained by chopping between the sky and a blackbody, with sky temperature assumed the same as that of the telescope. The November observations of positions 1 and 16 and both observations of position 30 are given.

III. DISCUSSION

a) Line Intensities and Extinctions

The observed line intensities may be found from Figure 1. In our narrow bandpass only the very brightest continuum sources are detectable. Continuum emission can be seen clearly only in positions 38 and 41, very close to IRc2, and in 17, which is on IRc2. In positions 25 and 44 it is not clear whether there is continuum or broad low-intensity emission. Since we could not detect continuum on position 3 (Paper I), the second possbility is more likely.

The extinction to the region of H_2 emission is not well known at this time. Estimates range from 12 magnitudes of visual extinction (Scoville et al. 1981) to 40 mag (Beckwith et al. 1979). If we apply Becklin et al.'s 1968 work on the extinction to the galactic center, the extinction at 12.28 μm would be 1.5±.5 mag if A_V=40 mag, or 0.45 ±.2 mag if A_V=12 mag. This would cause all intensities in Table 1 to be multiplied by factors of 4 or 1.5, respectively. Since the transition is optically thin, the column density of molecules in the v=0, J=4 state is given by $N(0,4)=\frac{4\pi I}{Ah\nu}$, where I is the intensity and $A=2.76\times10^{-9}\ s^{-1}$ (Dalgarno and Wright, 1972). N(0,4) derived from Table 1 would be of order $10^{20}\ cm^{-2}$ with no extinction correction, and four times that if A_V=40 is used.

From the 2 μm observations one can derive total column densities for the hot, 2000 K component of the H_2. The column density in the v=0, J=4 state is greater than that of the hot gas by factors which range from 5, if A_V=40 mag is used, to 20 with A_V=12 mag. Most of the 12 μm line emission must therefore come from gas too cool to emit at 2 μm. This observation is in qualitative agreement with shock excitation models (e.g. Hollenbach and Shull, 1977) which predict a gradual cooling from 2000 K to ∿100 K behind a shock.

b) Velocity Structure

In Figure 2, the line widths are shown schematically superimposed on Beckwith et al.'s (1978) map of the 2 μm v=1-0, S(1) emission. In several positions the line shape is too complex to be fitted by a simple Gaussian profile. We will discuss briefly the most striking features of the 12 μm lines, their breadth, symmetry, and peculiar shapes, and the pattern of lines around IRc9 (IRS2).

i) Width of the Lines

Observations of the 2 μm lines with high spectral resolution showed them to be quite broad, with FWHM as great as 85 km s^{-1} (NGN). It is difficult to reconcile such velocities with the commonly accepted shock excitation model, because H_2 dissociates at shock velocities >25 km s^{-1} (Hollenbach and McKee, 1980). The spectra of Figure 1 confirm the tentative results of Paper I that the 12 μm lines are at least as wide as the near-infrared lines and that the breadths must be due to motion of the gas rather than scattering as was suggested by Draine, Roberge and Dalgarno 1979. In some places, for example at position 1, the 12 μm line is somewhat broader than the 2 μm line measured at the same place. The slightly higher resolution of the 2 μm observations (20 km s^{-1} vs. 35 km s^{-1}) is not enough to explain this effect. It is likely that the apparent increase in width is due to the greatly lessened extinction at 12 μm, as will be discussed in the next section.

ii) Symmetry of the Lines

There is an obvious and important difference between the 12 and 2 μm line shapes. The most noticeable feature of the 2 μm lines is their asymmetry. Many have strongly enhanced blue sides, or suppressed red sides. The extent of the asymmetry varies from place to place, with positions on the very periphery of the region appearing essentially symmetric. There is not convincing evidence for systematic asymmetry in the 12 μm lines. The probable explanation for this is that the near infrared lines have part of the red-shifted emission suppressed by extinction within the emitting region (cf. NGN 1981). Such extinction could account for the observed differences if the gas is expanding from a center in the molecular cloud and there is obscuring material within the region of expansion. The red-shifted hydrogen would then be on the far side of the cloud and more heavily obscured. Consequently, emission on the red side of the 2 μm lines would be attenuated and the 12 μm lines would be broader and more symmetric. Absorption extending over the line centers could also cause an apparent blue-shift of peaks of the 2 μm lines relative to these at 12 μm, as is seen in some positions near the center of the region.

If the intrinsic line shapes at 12 and 2 μm are assumed to be the same, and the apparent differences are due entirely to extinction, the amount of extinction across the emitting region can be estimated. It is not clear how well-founded such an assumption would be; the 2 μm lines show considerable structure on the blue sides which may or may not be present at 12 μm. However, if the simple assumption is made that the 2 μm lines are intrinsically symmetric, at position 1, for example, there must be ∿1.25 magnitudes of extinction between the gas moving at

+50 km s^{-1} and -50 km s^{-1}. This would correspond to 12 magnitudes of visual extinction. The similarity of Scoville et al.'s (1981) value of A_V=12 mag for the total extinction is a coincidence only, as the value obtained here is the relative extinction between two regions of H_2 emission; presumably the 12-40 magnitudes previously reported from 2 μm measurements alone may lie in front of the emitting region.

iii) Complex Line Shapes

In Figure 1 there are several spectra which clearly cannot be produced by simple turbulent gas motions alone. One is position 30 (IRc9), where there is a second peak in the line at a blue-shift of about 60 km s^{-1} relative to the main peak. When the position was reobserved five weeks after the first spectrum, the blue peak appeared stronger compared to the main peak. The change in the spectrum is presumably not due to intrinsic variability, but rather to pointing errors, since apparently the blue component is very localized and hence the intensity quite dependent on pointing position. The other most interesting line shape is at position 33, where there is a pedestal structure, symmetric about zero velocity. This position shows emission over a full ±100 km s^{-1}, with a central spike no wider than the instrumental resolution. Finally, the extremely broad lines at positions 21 and 14 may have a pedestal shape as well.

iv) The region of IRc9

The gas and maser motions in the OMC have been carefully studied by several workers, including Genzel et al. (1981), Knapp et al. (1981), and Solomon, Huguenin, and Scoville (1981). All agree that the dynamics, specifically the high velocity motions, are dominated by flow expanding from the BN-KL-IRc2 region, although they disagree on the exact source. In the 12 μm line, an unexpectedly complex pattern of line shapes occurs within 15" of IRc9, 40" north of the supposed dynamical center.

At the position of IRc9 there is a double-peaked line. Close to it are the narrowest and broadest lines observed. In this region the line shapes change greatly from point to point, which does not occur anywhere else in Orion. Within 10" the line breadths go from 100 km s^{-1} to <35 km s^{-1}. In a sequence of slightly overlapping beams extending south to north (positions 33, 13, 39, 16), the line shapes change from a pedestal, to two broad red lines, to an unresolved line at +9 km s^{-1}. The emission disappears completely in position 8 and then reappears further north. There may be two components, one broad and one narrow, both of which occur in these spectra. There may in fact be three: a narrow one which looks like position 16, a blue-shifted, and a red-shifted component, each with half-widths of about 75 km s^{-1}. However the line shapes are interpreted, it is clear that there are peculiar motions in the area of IRc9. This must be reconciled with the large body of evidence that the primary source of the gas flow is considerably further south. IRc9 may have affected its immediate locality in a way that makes the flow appear differently, or it may be responsible itself for some high-velocity motions. The paucity of information on IRc9 makes difficult even speculation on such questions. Further analysis of the 12 μm data and comparison with observations at other wavelengths, of H_2 and of other molecules, may help clarify the gas motions in Orion, which now appear even more complicated than they have in the past.

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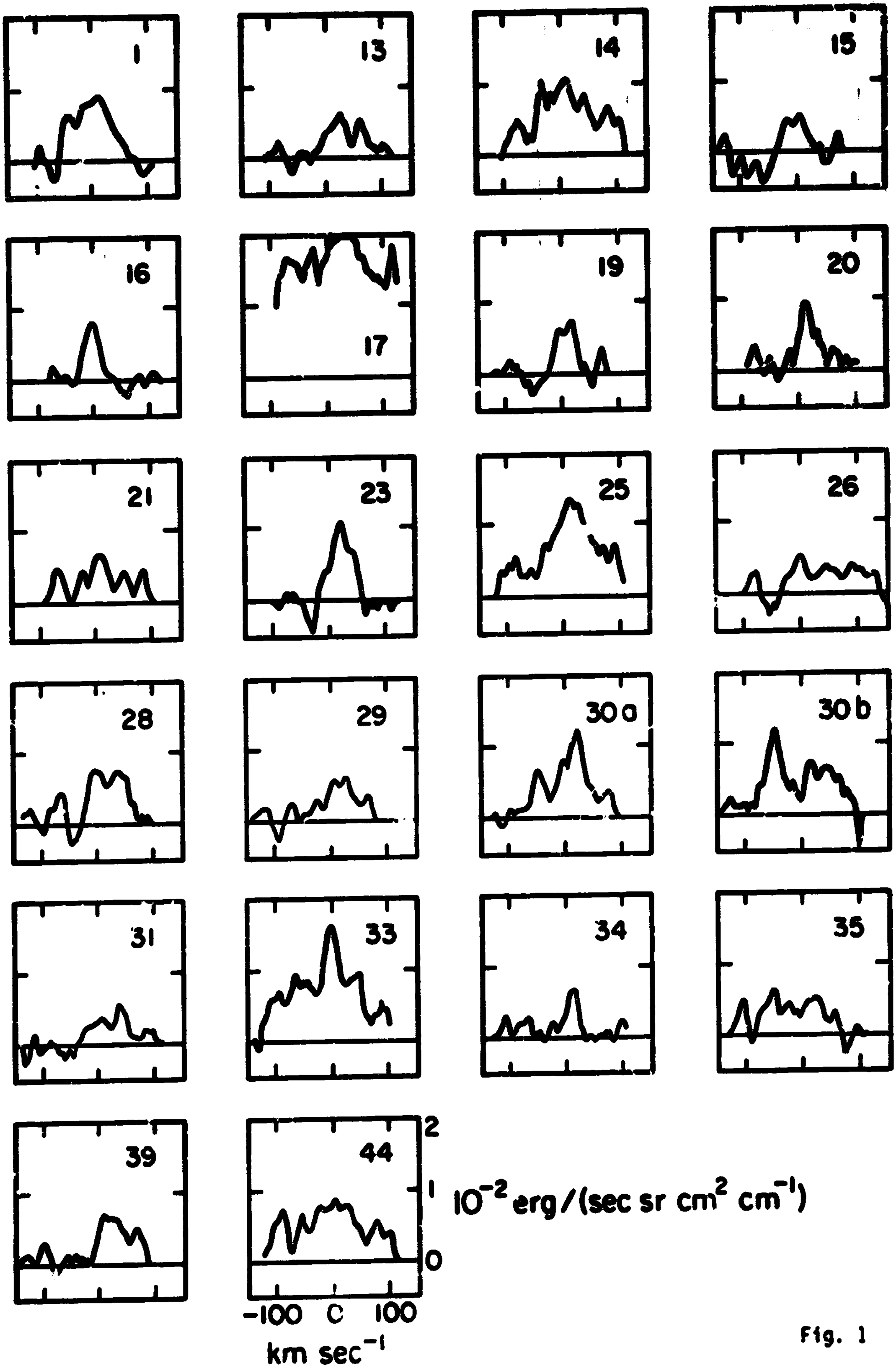
1
13
14
15
16
17
19
20
21
23
25
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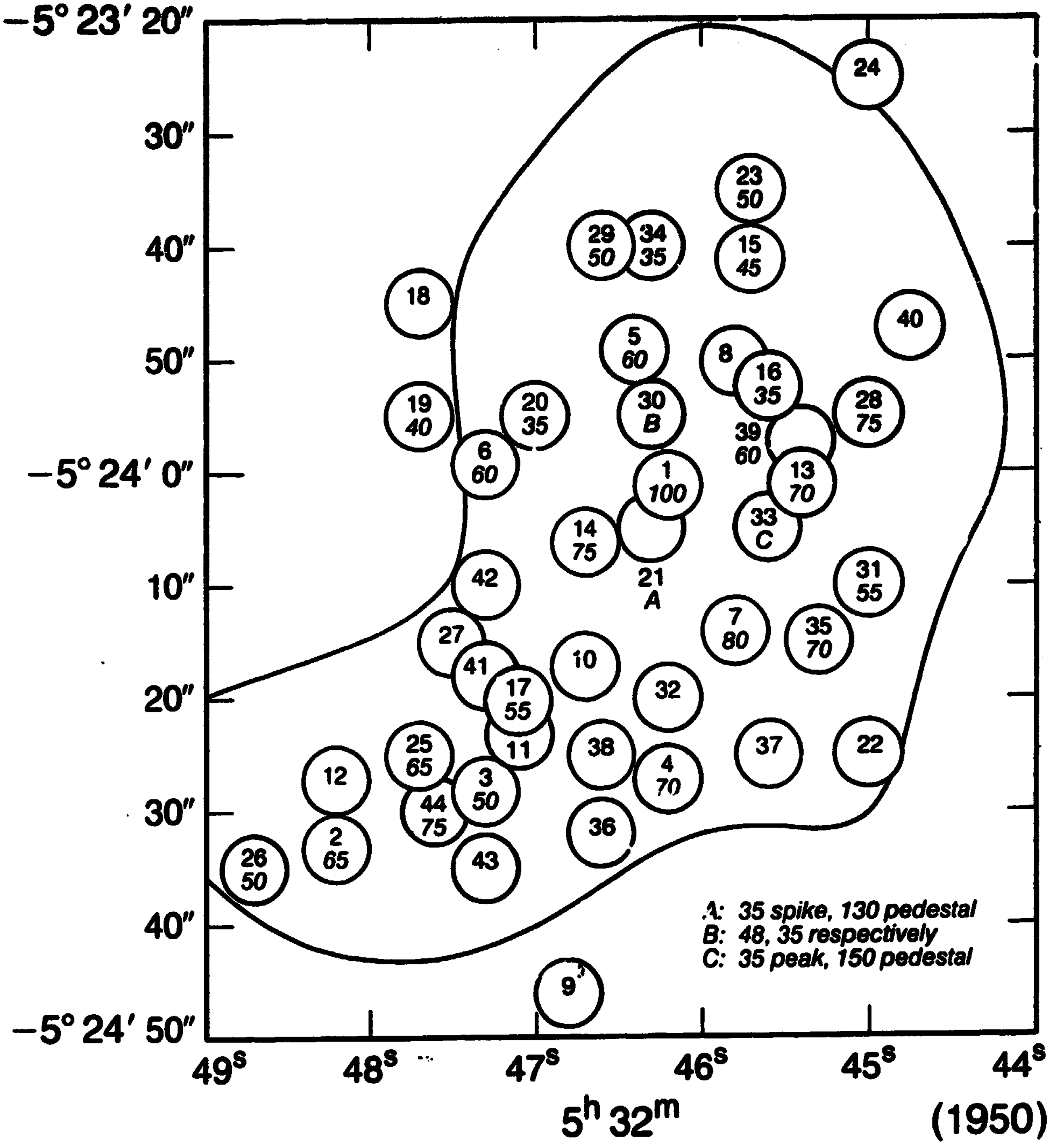
28
29
30a
30b
31
33
34
35
39
44
2
1
0
10^{-2} erg/(sec sr cm^2 cm^{-1})
-100
0
100
km sec^{-1}

Fig. 1



A: 35 spike, 130 pedestal
B: 48, 35 respectively
C: 35 peak, 150 pedestal

Fig. 2

FIGURE CAPTIONS

Figure 1. Spectra of the H_2 lines detected in the OMC from Mauna Kea. The numbers of each spectrum refer to the beam position (see Figure 2 or the Table for position location). All velocities are with respect to the LSR. σ is $1.7\text{x}10^{-3}$ erg/(sec sr cm^2 cm^{-1}) in a 35 km sec^{-1} resolution element. Position 30a is the November, 1980, measurement and 30b the January, 1981, result. There is a noticeable continuum only at position 17 which is on IRc2. At positions 25 and 44 there is possible continuum emission, but is more likely that the lines are very broad.

Figure 2. Locations where the S(2) line was looked for. The contour is the outermost contour from Beckwith et al.'s (1978) map of the v=1-0, S(1) emission made with a 13" beam. The circles are the beam size for the present measurements, the top number in each beam is the position number and the bottom, the FWHM. The FWHM is meant only as an indication of the overall trends, since many lines have complex shapes. Where there is no bottom number the line was not detected. For comments on positions 21, 30, and 33 see the text. Position 10 is located on the Becklin-Neugebauer object, position 17 on IRc2, and position 30 on IRc9.

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