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A submillimetre wavelength spectral line search of the Orion molecular cloud core

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Summary. A submillimetre wavelength molecular line search of the Orion molecular cloud has been made covering a total of about 5 percent of the frequency range 342.8–358.6 GHz. This search, coupled with our previous observations of submillimetre transitions in this cloud, has led to the detection of 22 transitions of 14 molecular species, of which 16 are reported here for the first time. No unidentified lines have been detected in the present search. Mapping observations have been obtained for several of the lines and, in the case of H₂CO, we have been able to compare the present data with that obtained from other telescopes, to estimate the density and abundance in the emitting region.

Key words: interstellar medium – molecules.

1. Introduction

The spectrum of the Orion molecular cloud shows very complex structure at millimetre wavelengths, containing the rotational emission lines from almost 70 molecular species, as well as strong continuum emission. High spectral resolution ($\Delta\nu \sim 1$ MHz) surveys of the molecular line emission at these wavelengths have recently been made in the frequency ranges 35–50 GHz (Ohishi, 1984), 72–91 GHz (Johansson et al., 1984), 83–109 GHz (Ohishi, 1984), 215–247 GHz (Sutton et al., 1985), and 260–285 GHz (Erickson et al., 1980). Some limited observations at submillimetre wavelengths have been made reported for specific lines by Keene et al. (1983), Padman et al. (1982), Phillips et al. (1980), Phillips and Huggins (1982), Wootten et al. (1983), Beichman et al. (1983), Koepff et al. (1982), White et al. (1981, 1982, 1986), Loren and Wootten (1985) and references therein. However, most of the submillimetre spectral region remains as yet unobserved.

Sensitive measurements at submillimetre wavelengths have been hampered by the relatively insensitive detectors, and lack of telescopes which are situated at an altitude above the absorptive water vapour in the atmosphere. In this paper we report the detection of many of the molecular lines which are expected to be moderately intense in the frequency range 342–359 GHz, plus some additional observations at 461 and 462 GHz. This search

is an extension of the earlier study of White et al. (1986), which dealt only with specific observations of HCN, HCO⁺, and CS.

2. The observations

The submillimetre search of the Orion molecular cloud core was carried out with the 3.8 metre United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. The observations were made during October 20–28 1984, using the QMC Submillimetre Wave Spectral Line receiver, mounted at the $f/9$ Cassegrain focus of UKIRT. This receiver has three separate cryogenically cooled front ends, optimised for the frequency ranges 220–260, 330–370, and 450–500 GHz. The front end mixers contain indium antimonide hot-electron detectors mounted in waveguide cavities, which are sensitive to vertically polarised radiation. The system noise temperatures were typically 300–400 K at 345 GHz, and 1000 K at 462 GHz. An on-axis television-guider system was used to acquire the source, the alignment of optical and submillimetre axes having been determined from continuum observations of Jupiter, Saturn and Venus. The pointing was measured to be good to 5". Observations of the moon and planets, coupled with sky-tips, were made to estimate the coupling of the telescope beam onto sources of known diameter. We estimate that η_{fss} , the forward scattering and spillover efficiency (Kutner and Ulich, 1981) was 0.88 at 345 GHz, and ≤ 0.6 at 462 GHz. The half-power beamwidth was measured to be 55" at 345 GHz and 43" at 462 GHz. All of the spectra were observed towards the position $RA(1950) = 05^{\text{h}}32^{\text{m}}47^{\text{s}}.0$ $DEC(1950) = -05^{\circ}24'23''$. Subtraction of the instrumental baseline was achieved by position switching every few minutes to a reference region at $RA(1950) = 05^{\text{h}}24^{\text{m}}27^{\text{s}}.0$ $DEC(1950) = -03^{\circ}24'17''$, determined to be free of significant molecular line emission. The zenith atmospheric transmission at 342–358 GHz was typically 0.7–0.8, and at 462 GHz was 0.3. The atmosphere was unusually wet for these observations, and the transmission was consequently poor, relative to that which we have normally encountered at these frequencies from Mauna Kea.

In order to compare the present data with that obtained from other telescopes for different transitions of the same molecular species, it is necessary to make several corrections to the observed antenna temperatures. To correct for coupling of the beam to an extended source, we have divided the chopper calibrated corrected antenna temperatures, T_A^* by η_{fss} . This provides a scale of corrected radiation temperature, T_r^* (Kutner and Ulich, 1981).

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This quantity does not, however, take account of the finite brightness distribution of a source. It is therefore necessary to divide T_r^* by another factor, η_c , which corrects for coupling of the angular size of the source into the telescope beam, giving an estimate of the brightness temperature for a particular line (Kutner and Ulich, 1981). In Fig. 1, the variation of η_c with source diameter is shown for the QMC receiver at 345 GHz. This calibration curve was derived initially from theoretical calculations (Lesurf, 1981) which model the receiver beam and UKIRT telescope configuration, and subsequently confirmed against observations of planets. Since the line emission from Orion originates from different sized regions in the cloud core dependent on which molecular species is observed, we are unable to calibrate the lines to a scale of brightness temperature, in a self-consistent way. Consequently, all results in this paper are expressed as T_r^* , unless otherwise stated.

The results of this search are summarised in Table 1. This lists the assumed line frequencies, in most cases taken from the compilations of Poynter and Pickett (1980), Lees et al. (1973), and Ziurys et al. (1982). We list the identification; transition

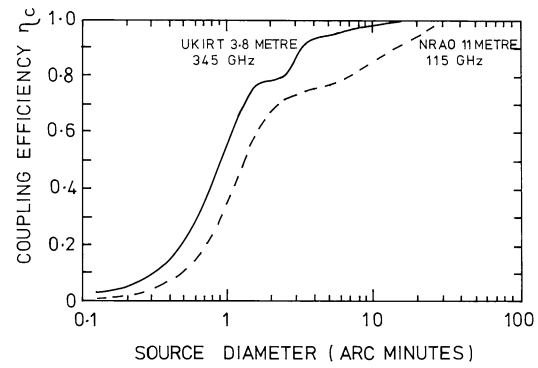


Fig. 1. Variation of coupling efficiency as a function of circular source size at 345 GHz for the QMC/UKIRT system. For comparison, similar quantities for the Kitt Peak 11 metre antenna (Kutner and Ulich, 1981) are shown. It has not yet proved possible to carry out such rigorous analysis at 460 GHz, and consequently all measurements close to this frequency in this paper are in T_r^*

Table 1

Frequency (GHz)	Species	Transition	T_r^* (K)	v (km s ⁻¹)	Δv (km s ⁻¹)	E (cm ⁻¹)	Search range (km s ⁻¹)	Comments
342.8833 ^a	CS	7-6	7.8	10.1	7.0	34		
343.3255	H ₂ ¹³ CO	5 _{1,5} -4 _{1,4}	1.3	9.0	5.2	31		
344.2003	HC ¹⁵ N	4-3	1.5?	?	?	17		
344.3106	SO	8 ₈ -7 ₇	13.5	9.0	22.	49		
344.905	SiO	8-7 $v=1$	<1.5	-	-	41	-45 +60	Non-detection
345.3398 ^a	H ¹³ CN	4-3	6.8	11.5	22.	17		Blended with SO ₂ ?
345.7046	SO	2 ₃ -2 ₁	<2.0	-	-	3	-70 +70	Non-detection
345.7960 ^a	CO	3-2	84.0	9.0	14.	12		
346.5285	SO	9 ₈ -8 ₇	10.5	9.5	28.	43		
346.9841	H ₂ C ¹⁸ O	5 _{4,2} -4 _{4,1}	<1.0	-	-	155	-10 +50	Non-detection
346.9976 ^a	H ¹³ CO ⁺	4-3	1.5	8.6	3.4	17		
347.3316	SiO	8-7 $v=0$	3.8	9.5	14.	41		
348.5319	H ₂ CS	10 _{1,9} -9 _{1,8}	<1.0	-	-	61	-1 +17	Non-detection
349.3381	CCH	4-3 7/2-5/2	4.5	8.7	3.5			
349.4006	CCH	4-3 9/2-7/2	7.3	9.4	3.5			
349.4266	CH ₃ CN	19-18 $k=2$	~1.5	?	?	117		
349.4467	CH ₃ CN	19-18 $k=1$	<1.0	?	?	117		Blended
349.4534	CH ₃ CN	19-18 $k=0$	2.3	8.0	8.5	117		
350.6877	CH ₃ OH	4 ₀ -3 ₋₁	3.0	9.0	7.0	14		
350.9051	CH ₃ OH	1 ₁ -0 ₀	6.4	8.5	12.8	0		
351.2572	SO ₂	5 _{3,3} -4 _{2,2}	3.4	10.0	13.	13		
351.7687	H ₂ CO	5 _{1,5} -4 _{1,4}	11.0	9.0	8.5	32		Low level wing
354.014 ^a	CO ⁺	3-2 7/2-5/2	<0.3	-	-		+2 +15	
354.5055 ^a	HCN	4-3	18.1	10.0	30.	18		Mostly plateau
356.7332 ^a	HCO ⁺	4-3	16.2	8.2	6.4	18		Plateau component present
357.8925	SO ₂	7 _{4,4} -7 _{3,5}	1.8		Blended	33		Lines blended together
357.9259	SO ₂	6 _{4,2} -6 _{3,3}			Blended	29		
358.6058	CH ₃ OH	4 ₁ -3 ₀	6.5	8.7	3.6	19		
461.0408	CO	4-3	53	-	-	23		T_A^*
462.4335	NH ₂	1 ₀₁ -1 ₁₀	<5	-	-		-6 +25	T_A^* upper limit

^a Line Parameters from White et al. (1986)

(either $J =$; or $F =$; or J_k or $J_{k-1,k}$; the lower state energy (cm^{-1}); and the values of peak T_r^* ; centre velocity and half-power linewidth determined from gaussian fits to the spectra. In addition, for those cases where the line was not detected, and an upper limit is given, the velocity range of the search spectrum is indicated. Finally, notes are added for particular cases. This table incorporates the line parameters measured by White et al. (1985) for eight previously detected submillimetre wavelength lines, so as to make a complete list of the lines detected at UKIRT over this frequency range.

In Fig. 2, spectra of the detected lines are shown. For a number of frequencies, observations were made using our maximum bandwidth of 127 MHz with 1 MHz filters (central frequencies were 344.300, 345.700, 345.796, 346.500, 347.315, 350.900, 351.750 and 357.900 GHz, corrected to an lsr velocity of 9 km s^{-1} for Orion). Higher spectral resolution ($\Delta v = 0.65$ or 1.0 km s^{-1} as shown in the spectra illustrated), and lower noise spectra were then obtained at frequencies corresponding to the lines detected in the wide-band observations, and in general these are illustrated in Fig. 2.

The detected lines can be divided into two categories; those with broad emission lines, which we arbitrarily define as having half-power linewidths greater than or equal to 10 km s^{-1} ; and those whose linewidths are narrower than this value. It has long been known that the plateau source in the core of the Orion molecular cloud has characteristic broad spectral lines associated with it (the so called ‘‘plateau emission’’); these are associated with energetic mass outflow. Lines with widths less than $\sim 10 \text{ km s}^{-1}$ are associated with the so called ‘‘spike’’ component, also known as the molecular ridge (Vogel et al., 1984). A number of lines in this survey show emission from both these cloud components. None of the narrow lines detected show characteristics of emission from the ‘‘hot core’’, which has a velocity of $5\text{--}7 \text{ km s}^{-1}$ (Beckman et al., 1982), although a contribution from this component may be present in some cases at a low level. Ohishi (1984) has attempted to classify the emitting zones even further, by characterising regions having different excitation temperatures.

3. The broad lines

The lines in this category include CO, SO, SO_2 , SiO, HCN and H^{13}CN . The CO $J = 3 - 2$ and $J = 4 - 3$, HCO^+ and HCN $J = 4 - 3$ lines have been discussed previously (Richardson et al., 1985 and White et al., 1986). The two lines of SO detected here exhibit broad spectral profiles extending over full widths greater than 50 km s^{-1} . The transitions have lower state energies of 43 and 49 cm^{-1} . The profiles resemble those emitted in the lower frequency transitions, having no obvious narrow spike component, but instead having a similar line shape to those seen in lower frequency transitions (Phillips and White, 1983). The three SO_2 lines detected are also characterised by the broad spectral profiles seen at lower frequencies (White and Phillips, 1983), although the signal to noise ratio of the submillimetre data is considerably worse. The 357 GHz lines are blended together (their frequency separation corresponds to 28 km s^{-1}). We note also that the SO_2 $13_{2,12} - 12_{1,11}$ line at 345.3386 GHz lies within 1.2 MHz of the H^{13}CN $J = 4 - 3$ rotational transition, and that both lines will also be blended together (see also Loren and Wootten, 1985). From the relative intensities of the $5_{3,3} - 4_{2,2}$ and $7_{4,4} - 7_{3,5}/6_{4,2} - 6_{3,3}$ blend, we estimate that the $\text{SO}_2/\text{H}^{13}\text{CN}$ blend has approximately a 1:3 contribution from the two lines respectively.

We have detected emission from the $J = 8 - 7$ $v = 0$ line of SiO. The line profiles show broad-winged emission in the $J = 3 - 2$ and $4 - 3$ transitions (Schwartz et al., 1982), with peak intensities corresponding to a flux density of 70 Jy. The present detection of the $v = 0$ line with a peak intensity of 3.8 K, corresponds to a flux density of 1500 Jy in the $55''$ telescope beam ($1 \text{ K} = 395 \text{ Jy}$). The spectral emission extends over a total velocity width of 30 km s^{-1} . We have also searched for the $v = 1$ transition, over a velocity range of 105 km s^{-1} , but were unable to detect emission greater than 1.5 K ($\sim 600 \text{ Jy}$) from the two $v = 1$ maser groups at -7 and $+15 \text{ km s}^{-1}$, which are prominent in the $v = 1$ $J = 1 - 0$, $2 - 1$ and $3 - 2$ transitions. From the interferometric mapping in the SiO $J = 2 - 1$ line (Wright et al., 1983), we estimate for a $5 \times 10''$ diameter source, the SiO $J = 8 - 7$ brightness temperature $\sim 130 \text{ K}$.

4. The narrow lines

The lines in this category include HCO^+ , CCH, CH_3CN , CH_3OH , H_2CO and H^{13}CO^+ . The H_2CO $5_{1,5} - 4_{1,4}$ line at 351.768 GHz, shows evidence for an intense spike component, as well as having plateau emission extending from -5 to $+30 \text{ km s}^{-1}$. Similar profiles have been reported by Wootten et al. (1984) and Loren and Wootten (1985) for several other transitions, but these show a much weaker plateau component relative to the spike intensity, and a narrower (by a factor of two) half power linewidth. If we adopt a similar calibration procedure as that of Wootten et al. (1984) to determine the brightness temperature for the spike component (i.e. applying a value of η_c appropriate to a $0.6'$ diameter source (see also Bastien et al., 1985)), we estimate the peak brightness temperature of the $5_{1,5} - 4_{1,4}$ transition to be 32 K. The corresponding values for the $3_{1,3} - 2_{1,2}$ transition is 10.2 K, and for the $4_{1,4} - 3_{1,3}$ transition is 20 K (Wootten et al., 1984). The brightness temperature of the spike component increases steadily with increase of lower state energy level.

We have mapped the spatial distribution of the $5_{1,5} - 4_{1,4}$ line in a single velocity channel centred at 9.0 km s^{-1} , with a channel width of 1 km s^{-1} . The map, obtained with $30''$ spacing, is shown in Fig. 3. For comparison the distributions of HCO^+ and CCH ($n = 4 - 3$, $J' - J = 9/2 - 7/2$) mapped in a similar way are shown. The H_2CO is unresolved to the N, E and W of the Orion molecular core, but is extended to the south, in a similar way to that of HCO^+ . There is a suggestion of this southward extension also in the H_2CO $4_{1,4} - 3_{1,3}$ distribution of Wootten et al. (1984), and the ^{13}CO map of Schloerb and Loren (1982). The present map does not extend sufficiently far northwards to cover the northern cloud (S3) reported by Bastien et al. (1985).

The H_2^{13}CO $5_{1,5} - 4_{1,4}$ transition at 343.325 GHz was detected in this survey with an intensity ratio $[\text{H}_2\text{CO}]/[\text{H}_2^{13}\text{CO}] = 8.5$. This ratio is similar to that measured for the $3_{1,2} - 2_{1,1}$ transition by Sutton et al. (1985), which has a value of 8.0. Similarly the ratio of antenna temperatures for these two isotopes is found to be 58 and 18, for the $2_{1,1} - 2_{1,2}$ (Bastien et al., 1985) and $2_{1,2} - 1_{1,1}$ (Kahane et al., 1984) transitions respectively. We have carried out an LVG calculation for an assumed kinetic temperature of 80 K, over a range of hydrogen densities and molecular abundance per unit velocity gradient, to compare the ratio of the peak antenna temperatures of H_2CO and H_2^{13}CO transitions measured with the same telescopes. We have searched

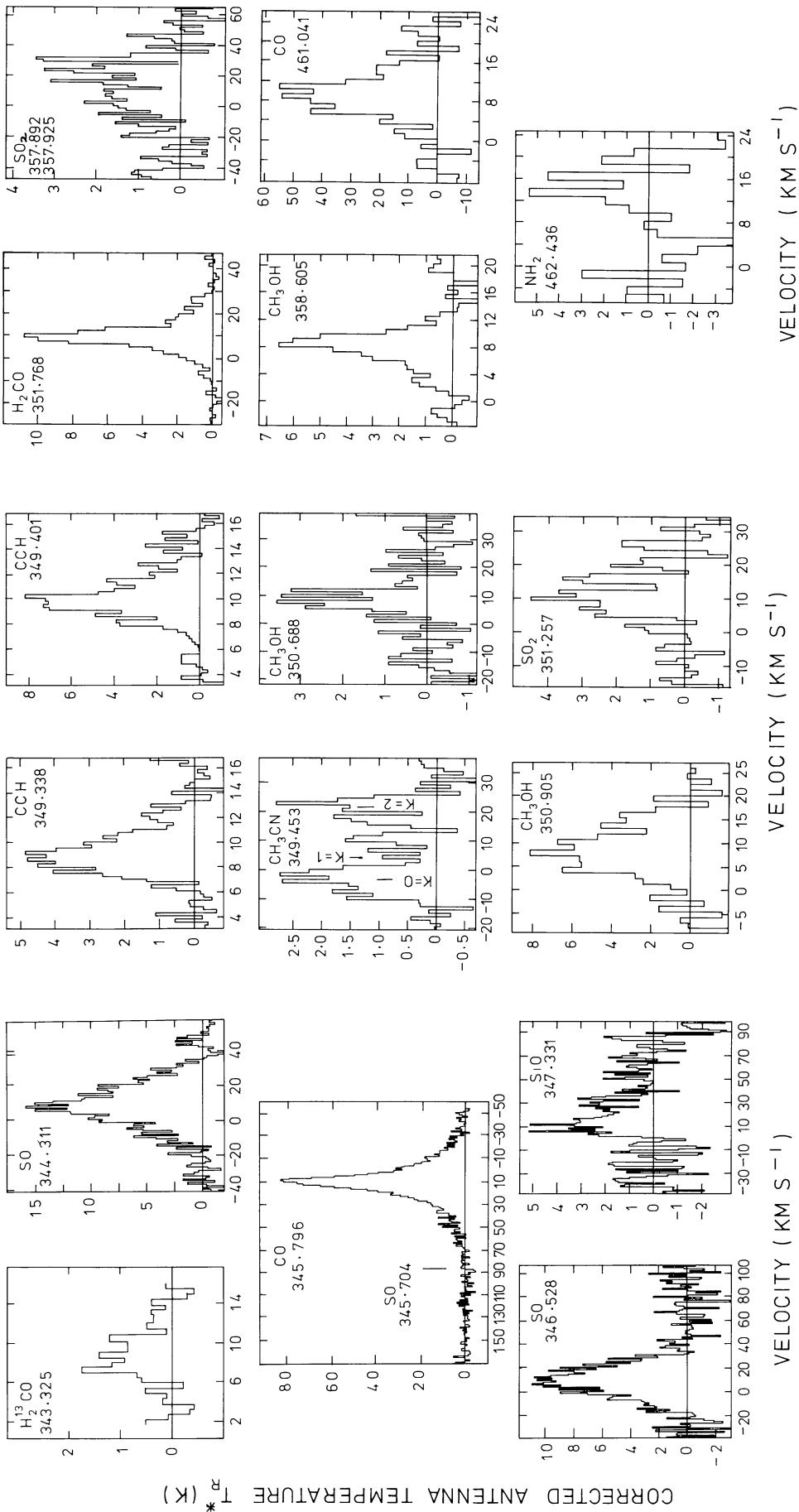


Fig. 2. Spectra of lines detected during this line search. The spectral resolution can be determined from the indicated channel widths of individual spectra. In most cases, the velocity scales are determined using the frequencies listed in Table 1. Exceptions to this are for CH₃CN and the SO₂ blend near 357.9 GHz, where the velocity scales are referred to 349.442 and 357.908 GHz respectively

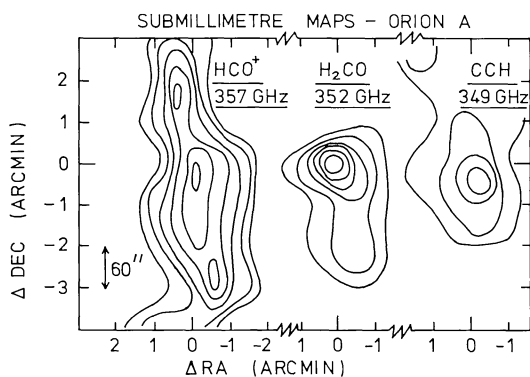


Fig. 3. Single velocity channel ($v = 9.0 \text{ km s}^{-1}$, $\Delta v = 1.0 \text{ km s}^{-1}$) maps of the Orion molecular cloud core sampled at half beam intervals

for a solution which agrees with the observed data for the $2_{1,1} - 2_{1,2}$, $2_{1,2} - 1_{1,1}$, $3_{1,2} - 2_{1,1}$, and $5_{1,5} - 4_{1,4}$ transitions, assuming an isotopic abundance ratio $C/^{13}C = 89$. The best fit solution is $n(\text{H}_2) = 2.5 \cdot 10^6 \text{ cm}^{-3}$, and $x/(dv/dR) = 4 \cdot 10^{-10} \text{ km}^{-1} \text{ s pc}$. This model solution predicts measured ratios of antenna temperature for $\text{H}_2\text{CO}/\text{H}_2^{13}\text{CO}$ for the $2_{1,1} - 2_{1,2}$, $2_{1,2} - 1_{1,1}$, $3_{1,2} - 2_{1,1}$ and $5_{1,5} - 4_{1,4}$ transitions of 55, 14, 7.9 and 7.9 respectively. These should be compared with the measured values of 58, 17.7, 8.0 and 8.5. To within the observational uncertainties, the model accurately reproduces the observed ratios over a wide range of frequencies. Under these conditions, the $5_{1,5} - 4_{1,4}$ transition has $\tau \approx 16$, and an excitation temperature of 73 K. This model then predicts a brightness temperature for the $1_{1,0} - 1_{1,1}$ transition of 8.1 K, which is in good agreement with the peak main beam brightness temperature of 9 K measured by Johnston et al. (1983) with the VLA. The derived best fit solution is thus in agreement with the analysis of Johnston et al. (1983), and Bastien et al. (1985), for simple LVG geometries. We point out that for the $5_{1,5} - 4_{1,4}$ transitions, the half power linewidth is about twice that of lower transitions. It is likely that this arises from a combination of increasing opacity in the higher lines, and from the blending of emission from the plateau and spike components.

The CCH transitions at 349 GHz appear as narrow lines having half-power line-widths of 3.5 km s^{-1} . Spectra were obtained for both the $N = 4 - 3$, ($J' - J) = 9/2 - 7/2$ and $7/2 - 5/2$ transitions, using the frequencies derived by Ziurys et al. (1982). These lines are further split into a blend of hyperfine components (Ziurys et al., 1982). The $(9/2 - 7/2)$ blend is predicted to be ~ 25 percent stronger than the $(7/2 - 5/2)$ blend. Our data show that for the Orion molecular cloud core, the measured intensities differ by about 60 percent, with the $9/2 - 7/2$ transition being the stronger. In contrast, at the “radical” position (3'N, 1'E), the two transitions are of similar intensity, as shown in Fig. 4. These latter spectra were observed at the same time as those towards the molecular cloud core, and we alternately took spectra at both positions, separated by an off source spectrum, so that the relative intensities of individual lines at the two positions is well determined. These differences probably reflect a difference of excitation at the two emission sites.

From the mapping shown in Fig. 3, the distribution of CCH in the cloud core is slightly less extended than that of HCO^+ or H_2CO , although there is a suggestion of elongation along a N-S direction. The intensity then increases again towards the radical position.

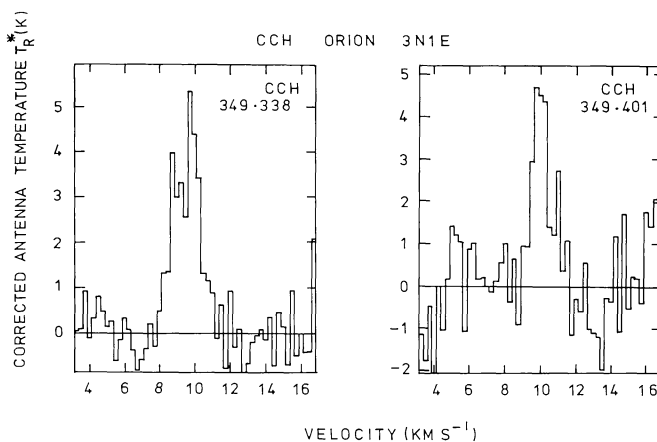


Fig. 4. Spectra of CCH towards the “radical position” 3N1E of the centre of the Orion cloud core. The velocity resolution is 0.25 km s^{-1}

Three methanol lines were observed in the survey, corresponding to the $4_0 - 3_1$, $1_1 - 0_0$, and $4_1 - 3_0$ transitions. There is considerable variation in the half-power line widths of these lines, which show a steady decrease as the lower state energy level increases. The $4_1 - 3_0$ line at 358.6 GHz, has a pronounced blue wing, extending to about 0 km s^{-1} . This is similar to the shape of a number of the methanol spectra from the Nobeyama survey (Ohishi, 1984), where this component is identified with the hot core component at a velocity of 4 km s^{-1} . Dr. M. Ohishi has kindly used his statistical equilibrium model (Ohishi, 1984) to examine the possibility that any of these submillimetre wavelength lines are masing. He finds that the $4_1 - 3_0$ transition can show weak maser action, although under the excitation conditions relevant to the Orion cloud core, such maser action would be weak. However, the excitation temperature for this transition can be much higher than that of the other two thermally excited transitions, explaining the higher observed antenna temperature.

We have detected the $J = 19 - 18$, $k = 0, 1$, and 2 transitions of methyl cyanide. The lines are blended together, but the $k = 0$ and 2 lines are clearly identifiable. The $k = 1$ line is considerably weaker than the other two. The lower state energy level for the $k = 0$ line is 117 cm^{-1} . Observations of lower rotational transitions have been summarised by Loren and Mundy (1984), who show that the lines contain emission for both the ambient and hot-core components.

5. Non-detections

The non-detections in the search are mostly of lines which either have lower state energy levels that are relatively high, or of transitions in which the line strengths are very small. The non-detections include the HC^{15}N isotope, which based on our previous modelling of the $J = 4 - 3$ HCN line (White et al., 1986), is expected to be just below our detection threshold, and this applies similarly for $\text{H}_2\text{C}^{18}\text{O}$. The $\text{SO } 2_3 - 2_1$ transition at 345.7046 GHz has a $\Delta k = 2$ jump, and consequently the transition line strength is low, and the line should be extremely weak. No evidence was found for the existence of any lines which could not be identified with known interstellar molecular species, although we note that our search was biased against serendipitous discoveries.

6. Conclusions

This submillimetre wavelength molecular line search, together with the data from our earlier session (White et al., 1986), has led to the detection of 22 transitions of 14 molecular species at submillimetre wavelengths, of which 16 are reported here for the first time. This very limited survey (covering ~ 5 percent of the total frequency range between 342.8 and 358.6 GHz) is an indicator of the rich and diverse range of astrophysical information that will be available to the next generation of submillimetre wave telescopes. The H_2CO data indicate that in the core, $n(\text{H}_2) \geq 2.5 \cdot 10^6 \text{ cm}^{-3}$ in the spike component. Also for this transition, the plateau becomes more prominent than at lower frequencies.

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