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Observations of submillimetre lines of CH_3OH, HCN, and H_2CO in comet P/Swift–Tuttle with the James Clerk Maxwell Telescope

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Abstract. We present submillimetre molecular line observations of comet P/Swift–Tuttle (1992t = 1992 XXVIII) which were undertaken on 7 and 8 December 1992 with the James Clerk Maxwell Telescope (JCMT). Three molecules were detected: (1) HCN through its J (4–3) rotational line at 354.505 GHz; (2) H_2CO through its 5_{15}–4_{14} ortho line at 351.769 GHz and (3) CH_3OH through several of its J (7–6) transitions at 338 GHz and one line at 341 GHz. The lines are blueshifted with respect to the comet rest velocity, which is indicative of preferential outgassing towards the Sun. The relative intensities of the CH_3OH rotational lines show that the population distribution can be described by a rotational temperature of 45 ± 7 K, although deviations from thermal equilibrium are present. The comparison with an out-of-equilibrium model suggests that the collisional region where thermalization occurs is larger than is expected in an isotropic coma where neutral–neutral collisions prevail. The model is able to reproduce most of the observed methanol line intensities. From these observations, we derive production rates of $Q(\mathrm{HCN}) = 1.3 \times 10^{27}$ s^{-1}, $Q(\mathrm{H_2CO}) = 5 \times 10^{27}$ s^{-1} and $Q(\mathrm{CH_3OH}) = 2 \times 10^{28}$ s^{-1}, assuming direct release from the nucleus and isotropic sublimation. This corresponds to molecular abundances with respect to water of 0.3, 1 and 4%, for HCN, H_2CO and CH_3OH, respectively.

1. Introduction

Comet P/Swift–Tuttle is a Halley-class comet which is associated with the Perseid meteor stream seen each year in August. P/Swift–Tuttle (1862 III) was observed as a bright object of magnitude 2 in its August 1862 perihelion passage. The date of its return was uncertain (see Marsden, 1973) until it was recovered on 26 September, 1992 (IAU Circ. N° 5620; comet 1992t = 1992 XXVIII). The comet passed perihelion on 12 December, 1992, at 0.96 AU from the Sun. This passage was not as favourable as the preceding one, because at perihelion the comet was at 1.57 AU from the Earth, on the other side of the Sun, and the closest approach to Earth was at 1.17 AU on 8 November (which is to be compared to 0.2 AU for the 1862 passage). However, the gas production rate of this comet, as measured from the observations of the OH radical in the radio (Bockelée-Morvan *et al.*, 1993) and in the UV (A'Hearn *et al.*, 1992; Feldman *et al.*, 1993), reached 5×10^{29} s^{-1} near perihelion. This makes this comet one of the brightest of the decade, not much less than P/Halley (which exceeded 10^{30} s^{-1}), and a good target for state-of-the-art observations.

Millimetre and submillimetre spectroscopy recently have proved to be a powerful method for identifying key molecular constituents of cometary atmospheres, to measure their abundance, and to study their kinematics. After the observations of HCN J(1–0) at 89 GHz in P/Halley at several radio telescopes (Crovisier and Schloerb, 1991), the identifications at millimetre wavelengths of formaldehyde, of several transitions of methanol and of hydrogen sulphide were made at the IRAM 30-m telescope (Bockelée-Morvan *et al.*, 1991; Colom *et al.*, 1992), and the first successful submillimetre spectroscopic observations of comets were obtained on comet Levy 1990 XX at the Caltech Submillimeter Observatory (CSO) by Schloerb and Ge (1992a), resulting in the detection of the HCN J(4–3) and H_2CO 5_{15}-4_{14} transitions.

We report here submillimetre molecular observations of comet P/Swift–Tuttle (1992 XXVIII) with the James Clerk Maxwell Telescope (JCMT), a 15-m antenna located at Mauna Kea (Hawaii). This was the first time molecular spectroscopy of comets was achieved with this instrument, although cometary continuum observations

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were made on several occasions with the JCMT (Jewitt and Luu, 1992).

2. Observations

The comet was tracked (and the receiver local oscillator was tuned) according to an ephemeris based upon the orbital elements of MPC 21235, kindly supplied before publication by B. Marsden. Subsequent orbital elements were computed by Marsden (quoted in Marsden and Williams, 1993) which only differ by 2″ from the positions used for the JCMT observations. The half-power beam width was 14″. The pointing was checked by observing Uranus which was only about 20° from the comet; pointing errors were 2–3″. For checking purposes, comparison spectra were obtained on the galactic source G34.2 using the same instrumental set-up.

First shifts were alloted on U.K. Service Observing Time on 22, 26 and 27 November. They were unsuccessful due to bad weather. The comet was then observed on 6, 7 and 8 December between 3 and 5h UT (which was the short time interval after sunset when the comet was at elevation greater than 20°). On 6 December, we tried to use frequency switching, but we had baseline problems which could not be solved. On 7 and 8 December, we changed to beam-switching with a throw of 1′ and a rate of 1 Hz.

All observations were made using the "B3i" receiver, which operates at 300–380 GHz with a SIS detector. Typical receiver noise temperatures were 200 K and system noise temperatures were 750 K. We used the AOSC (acousto-optical) spectrometer, which covers a total bandwidth of 500 MHz with 2048 channels and an effective resolution of 330 kHz (corresponding to approximately 0.29 km s^{-1}). The observations were made using the double-sideband mode with frequency setups chosen to observe molecular transitions in the two sidebands, which are separated by 3 GHz (for example, the HCN J(4–3) at 354 GHz and the H_2CO 5_{14}–4_{14} at 351 GHz transitions were observed simultaneously). To confirm that the lines were in the correct sideband, observations were made at two frequencies separated by 10 MHz.

On 7 December, the receiver was tuned to 338.5 GHz (lower sideband) to cover several lines of the J(7–6) series of CH_3OH in both sidebands. After 3000 s of integration (total of "on" and "off" positions), seven lines were clearly detected with a signal-to-noise ratio larger than 5. The 8 December observation was devoted to the HCN J(4–3) at 354 GHz and the H_2CO 5_{15}–4_{14} at 351 GHz transitions, which were detected with high signal-to-noise ratios in only 1800 s of integration. After these observations, an attempt was made to observe the comet in the continuum; the result was successful and will be reported elsewhere (Jewitt, in preparation).

A summary of the observational parameters is given in Table 1. The spectra are shown in Figs 1–3. The frequency calibration of the AOS was slightly incorrect. The frequency and velocity scales were improved according to the Appendix. A list of the detected lines and of their intensities is given in Table 2. An unidentified feature (labelled (?) in Fig. 1) is present at the 4-σ level in the 338 GHz spectrum, at 338,311.71 MHz (lower sideband, for both receiver settings, although more marginally in one of them) or 341,676.6 MHz (upper sideband, only for one receiver setting). No molecular lines could be found at these frequencies in Lovas (1992) or in other line compilations. The line width of the feature is approximately half that of the CH_3OH, H_2CO and HCN lines. Therefore a cometary origin of this feature is unlikely, although we cannot definitely exclude it.

3. Analysis

3.1. CH_3OH

The value of measuring several line intensities of the same species is that it permits an estimate of the rotational population distribution. This distribution provides clues about the excitation conditions and improves the accuracy of determinations of molecular production rates. Information on the rotational population distribution of water was obtained from the analysis of its ro-vibrational lines at 2.7 μm detected in P/Halley using the KAO (Weaver *et al.*, 1987; Bockelée-Morvan and Crovisier, 1987). Constraints on the excitation of methanol were derived from the observations of several rotational transitions at 97, 145 and 165 GHz in comets Austin (1990 V) and/or Levy (1990 XX) (Bockelée-Morvan *et al.*, 1994b).

This is the first time that the J(7–6) rotational transitions of methanol at 338 and 341 GHz were detected in a comet. In addition to the detected lines, several other J(7–6) transitions fall within the observed bandwidth. Their frequencies and 3-σ upper limits are given in Table 2. The observed lines connect (J, K) rotational levels with energies between 49 and 206 K. They are expected to complement the observations at 145 and 165 GHz performed two weeks earlier with the IRAM 30-m telescope that sampled rotational levels of lower energy ($E < 56$ K) (Despois *et al.*, 1994).

In order to study the observed relative line intensities, we used the rotation diagram method commonly used for interstellar molecular line studies and recently applied to the CH_3OH lines observed in comets Austin (1990 V) and Levy (1990 XX) (Bockelée-Morvan *et al.*, 1994b). This method is based on the fact that, under optically thin conditions, the observed line intensity is proportional to the column density $\langle N_u \rangle$ within the upper state of the transition. If one assumes that the population distribution among the levels sampled by the lines can be described by a rotational temperature T_{rot}, a plot of the natural logarithm of the line intensities vs energy of the upper levels should produce a straight line whose intercept at $E_u = 0$ is proportional to the molecular density $\langle N \rangle$ and whose slope gives T_{rot}. Such rotation diagrams provide a probe of the population distribution by yielding both an estimate of T_{rot} and a test for deviations from thermal equilibrium. The latter would cause deviations from a straight line in the plot. When the optical depth is small and LTE conditions are fulfilled, these diagrams allow us to derive the molecular column density almost inde-

Table 1. Observational parameters

Date	Lower sideband (MHz)	Upper sideband (MHz)	T_{rec} (K)	T_{sys} (K)
92/12/07	338,250–338,750	341,250–341,750	220	800
92/12/08	351,430–351,930	353,430–353,930	160	700

Distance to Earth:	1.48 AU
Distance to Sun:	0.96 AU
Half-power beam width:	14″
Efficiency:	0.50

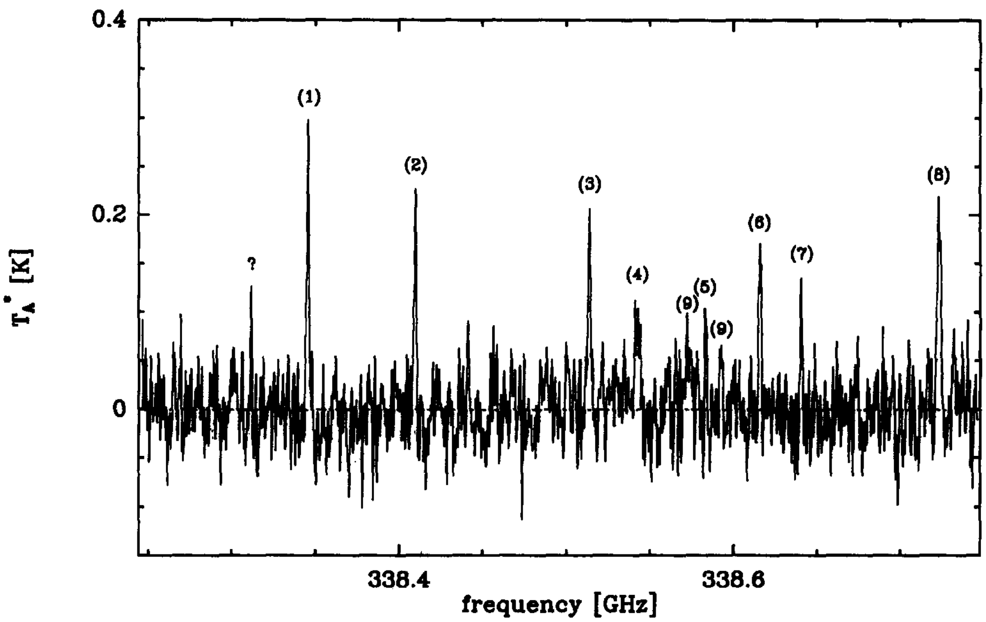

Fig. 1. The spectrum of CH_3OH observed at 338 GHz in comet P/Swift–Tuttle on 7 December 1992. A recalibration of the frequency scale has been performed (see the Appendix). Hanning smoothing has been applied and the spectral resolution is 0.5 MHz. The detected lines are labelled from (1) to (9) and their assignations are given in Table 2. The CH_3OH line at 341.4156 GHz detected in the upper sideband of the receiver appears on this spectrum at two frequencies (labels (9)), since the frequency set-up was changed by 10 MHz during the observations. The line labelled by (?) at 338.3117 GHz is discussed in Section 2

pendently of any model assumption about the excitation conditions.

The rotation diagram inferred from eight among the nine 338 and 341 GHz detected lines is shown in Fig. 4. The line at 338.512 GHz, which corresponds to three blended transitions with upper states differing in energy, was not used in this analysis. However, we have taken into account the unseparated transitions at 338.722 GHz (Table 2) starting from the (7, 2) and (7, −2) E levels at 87.3 K and 90.9 K, respectively, by attributing half of the observed intensity to a virtual level of intermediate energy (89 K). We also introduced a virtual level in order to account for the unseparated transitions at 338.541 and 338.543 GHz (Table 2), although a thorough analysis of the line shape should constrain the relative intensities of the transitions in the future. The 3-σ population upper limits obtained from the undetected lines are also shown in Fig. 4 (triangles), but they were not used for the derivation of T_{rot}.

The rotation diagram shown in Fig. 4 is normalized so that the slope of the straight line is $1/T_{rot}$ and the intercept at $E_u = 0$ K gives $\langle N \rangle / Z\ (T_{rot})$ in LTE conditions, where $Z\ (T_{rot})$ is the partition function at T_{rot}. We infer $T_{rot} = 45 \pm 7$ K, $\langle N \rangle / Z = 3.3 \pm 1 \times 10^{11}$ cm^{-2}, and $\langle N \rangle = 1.0 \pm 0.4 \times 10^{14}$ cm^{-2} taking into account the error on the partition function introduced by T_{rot}. In contrast, a rotational temperature of 80 K is derived from the observations at 145 and 165 GHz performed at IRAM (Despois *et al.*, 1994). Figure 4 shows that small—but significant—deviations from thermal equilibrium are present, suggesting that the observations were sampling molecules outside the inner collision-dominated region. The level populations determined from the 3-σ upper limits are consistent with the average population distribution. It is now interesting to test whether the measured LTE deviations and rotational temperature are expected from excitation models.

A model for the excitation of methanol in cometary atmospheres was developed by Bockelée-Morvan *et al.* (1994b), in order to analyse the millimetre observations

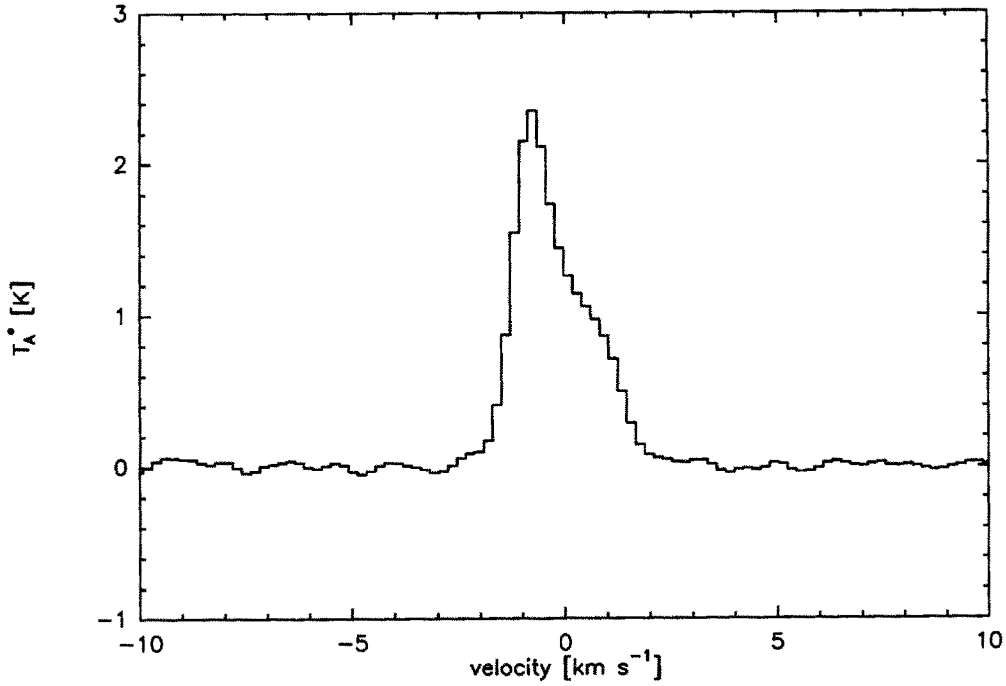

Fig. 2. The J (4–3) HCN line at 354.505 GHz observed in comet P/Swift–Tuttle on 8 December, 1992. A recalibration of the frequency scale has been performed (see the Appendix). The spectral resolution is 0.5 MHz. The velocity scale is with respect to the nucleus velocity

of comets Austin (1990 V) and Levy (1990 XX). This model takes into account collisional excitation, radiative excitation of the fundamental band of vibrations by the I.R. solar radiation field and radiative decay. Collisional excitation is modelled very simply assuming that the collision rates scale as the product of a collisional cross-section times the water density. The model computes the evolution of the rotational population distribution from the inner coma, dominated by collisions, to the outer coma, where a radiative fluorescence equilibrium takes place, using the collisional cross-section σ_{coll} and the kinetic temperature T_{kin} as free model parameters. The analysis of the observations of comet Austin and Levy was conducted by comparing observed and modelled rotation diagrams (Bockelée-Morvan *et al.*, 1994).

The same approach was used for the 338 and 341 GHz

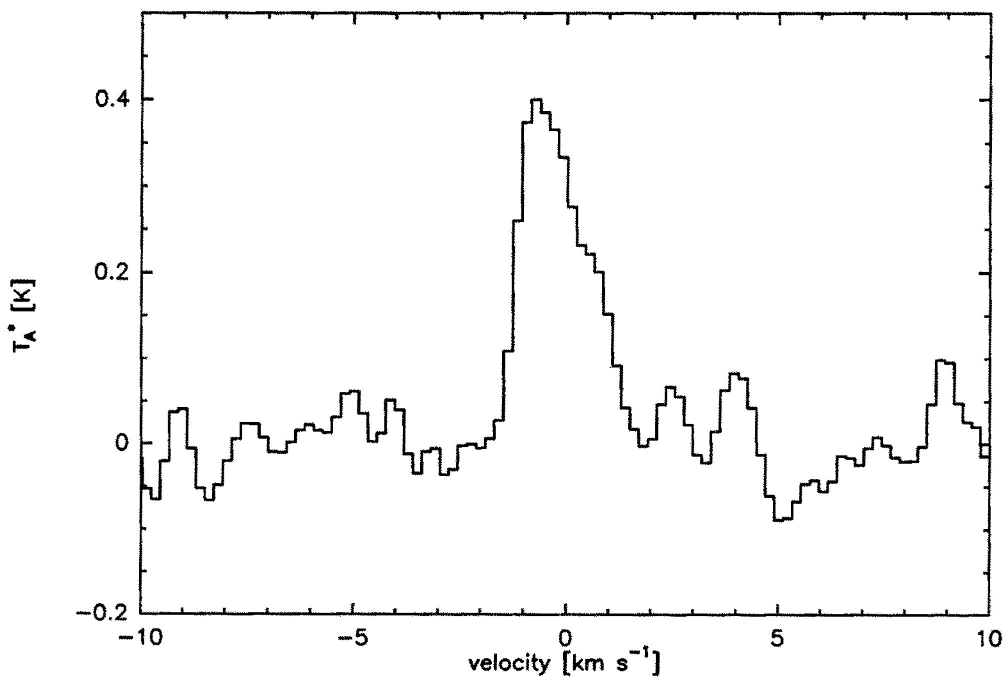

Fig. 3. The 5_{15}–4_{14} H_2CO line at 351.669 GHz observed in comet P/Swift-Tuttle on 8 December 1992. A recalibration of the frequency scale has been performed (see the Appendix). The spectral resolution is 0.5 MHz. The velocity scale is with respect to the nucleus velocity

Table 2. Observed molecular transitions

	Transition	Frequency (MHz)	$T_A^* \, dv$ (K km s^{-1})	Label e
CH_3OH	(7,-1)–(6,-1)E	338,344.6 a	0.43±0.04	(1)
	(7, 6)–(6, 6)E	338,404.6	<0.12	
	(7, 0)–(6, 0)A	338,408.7	0.37±0.05	(2)
	(7,-6)–(6,-6)E	338,430.9	<0.12	
	(7, 6)–(6, 6)A+	338,442.3	<0.12	
	(7, 6)–(6, 6)A–	338,442.3	d	
	(7,-5)–(6,-5)E	338,456.5	<0.12	
	(7, 5)–(6, 5)E	338,475.3	<0.12	
	(7, 5)–(6, 5)A–	338,486.3	<0.12	
	(7, 5)–(6, 5)A+	338,486.3	d	
	(7,-4)–(6,-4)E	338,504.1	<0.12	
	(7, 2)–(6, 2)A–	338,512.8	0.33±0.04	(3)
	(7, 4)–(6, 4)A+	338,512.6	d	
	(7, 4)–(6, 4)A–	338,512.6	d	
	(7, 4)–(6, 4)E	338,530.2	<0.12	
	(7, 3)–(6, 3)A+	338,540.8	0.25±0.05	(4)
	(7, 3)–(6, 3)A–	338,543.2	d	
	(7,-3)–(6,-3)E	338,559.9	<0.12	
	(7, 3)–(6, 3)E	338,583.2	0.12±0.03	(5)
	(7, 1)–(6, 1)E	338,615.0	0.25±0.04	(6)
	(7, 2)–(6, 2)A+	338,639.9	0.14±0.04	(7)
	(7, 2)–(6, 2)E	338,721.6	0.50±0.04	(8)
	(7,-2)–(6,-2)E	338,722.9	d	
	(7, 1)–(6, 1)A–	341,415.6	0.23±0.04	(9)
H_2CO	5_{15}–4_{14}	351,768.6 b	0.75±0.04	
HCN	J(4-3)	354,505.5 c	4.16±0.04	

a From Anderson *et al.* (1990); typical rms error is 0.1 MHz
b From Lovas (1992)
c From Lovas (1992); this transition consists of six hyperfine components, the three main ones (95% of the intensity) being within 0.11 MHz of the average frequency
d Blended with the previous line; the listed intensity is that of the blend
e Labels for Fig. 1

lines of methanol detected in P/Swift–Tuttle. The evolution of the rotation temperature within the $J = 7$ levels sampled by the observations was computed as a function of distance to nucleus for various sets of parameters (σ_{coll}, T_{kin}), assuming a water production rate of 5×10^{29} s^{-1} (Bockelée-Morvan *et al.*, 1994a). The model predicts that T_{rot} evolves from $T_{rot} = T_{kin}$, in the inner coma, to $T_{rot} = 15$ K, in the outer coma. T_{rot} deviates from T_{kin} at 400 km from the nucleus when $\sigma_{coll} = 10^{-14}$ cm^2, and at 1500 km when $\sigma_{coll} = 10^{-13}$ cm^2. The distance at which thermal equilibrium breaks down scales roughly as the square root of the collisional cross-section and the water production rate. The field of view was 15,000 km in diameter for the observations of P/Swift–Tuttle at JCMT. Calculation of the relative contributions of concentric shells to the observed main beam brightness temperatures shows that the observations sample the excitation conditions present at distances of approximately half the beam width, i.e. at 7500 km from the nucleus. The comparison between the rotational temperatures computed at 7500 km and the measured value of 45 K indicates that the kinetic temperature of the gas in the region where the last thermalizations occurred is larger than 45 K. On the basis of rotational temperature considerations, the model also predicts that the observed population distribution is not thermal unless the collisional cross-section is larger than 2×10^{-12} cm^2. On the other hand, the observed rotational temperature, when compared to model predictions with realistic T_{kin} values, suggests that the collisional cross-section is much larger than the value of 10^{-14} cm^2 estimated for neutral–neutral collisions. A similar result was obtained from the observations of methanol in comets Austin and Levy (Bockelée-Morvan *et al.*, 1994b). In fact, several sets of parameters (σ_{coll}, T_{kin}) could explain the observed T_{rot}, with σ_{coll} increasing as T_{kin} decreases. In particular the set $T_{kin} = 80$ K and $\sigma_{coll} = 10^{-13}$ cm^2 gives $T_{rot} = 50$ K at 7500 km from the nucleus, in good agreement with the data.

In order to test whether the model can reproduce the observed LTE deviations, the rotation diagram technique was applied to modelled intensities. These intensities were established by volume integration within the instrument beam, as explained in Crovisier (1987) and Bockelée-Morvan and Crovisier (1992), taking into account the radial evolution of the level populations and assuming a Haser density distribution for water and methanol. The model results presented in Fig. 4 assumes $T_{kin} = 80$ K, $\sigma_{coll} = 10^{-13}$ cm^2, $Q(H_2O) = 5 \times 10^{29}$ s^{-1} and $Q(CH_3OH) = 1.9 \times 10^{28}$ s^{-1}. The methanol life time was taken to be 70,900 s (Bockelée-Morvan *et al.*, 1994b) and the expansion velocity to be 0.8 km s^{-1}. The modelled rotation diagram provides a good fit to the data and

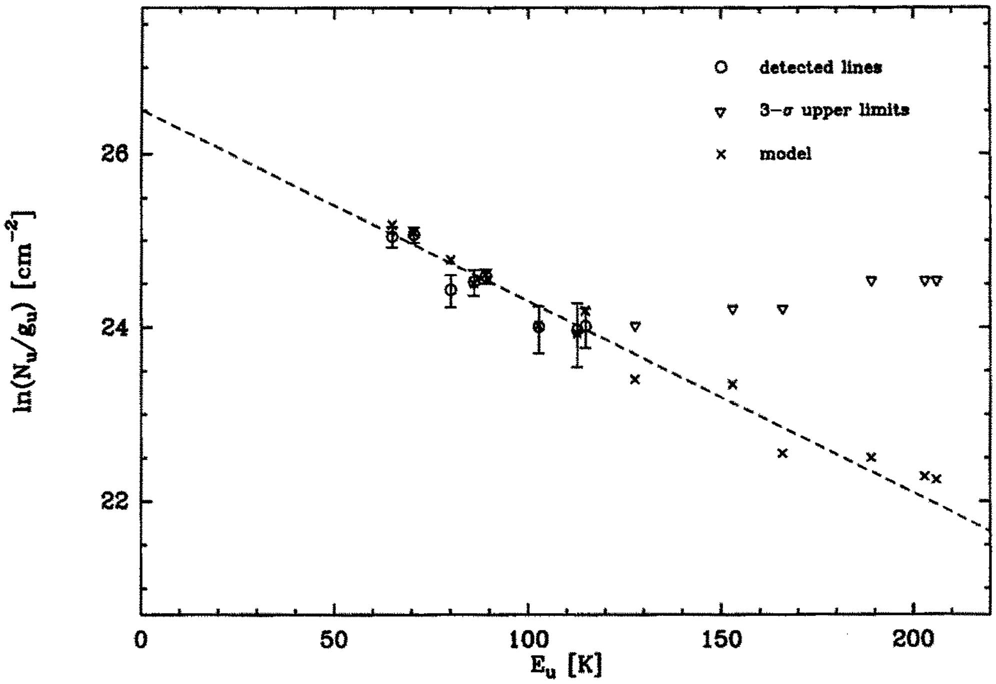

Fig. 4. LTE rotation diagram of CH_3OH in comet P/Swift–Tuttle derived from the detected lines at 338 and 341 GHz (circles). The dashed straight line corresponds to a rotational temperature of 45 ± 7 K. Triangles refer to the undetected lines and are 3-σ upper limits (only (J, K) levels with $| K < 6 |$ are plotted). A rotation diagram derived from model calculations is shown with crosses, for comparison. In this model the collisional cross-section is 10^{-13} cm^2, the kinetic temperature is 80 K and the methanol production rate is 1.9×10^{28} s^{-1} (see also text)

explains most of the LTE deviations. The populations predicted for the upper levels of the undetected transitions are in agreement with the observed 3-σ upper limits. This ability to reproduce the observed line intensities shows that the excitation of methanol is basically well understood. A more sophisticated model is needed, however, to go further in the interpretation of these data. Indeed, collisions by electrons are expected to play a major role in the excitation of methanol (Xie and Mumma, 1992). The coma of P/Swift–Tuttle is strongly asymmetric, as evidenced from the molecular line shapes (e.g. Colom *et al.*, 1993; Schloerb *et al.*, 1993) and the morphology of the dust coma (Yoshida *et al.*, 1993; Jorda *et al.*, 1994). As a result, local water densities were probably underestimated in the present work. The introduction of these two effects should improve the description of the collision-dominated coma and permit an independent determination of the kinetic temperature.

The methanol production rate derived from the 338 GHz lines is 1.9×10^{28} s^{-1} on 7 December. Independent evaluations are available for this period from infrared observations of the 3.52 μm band. Hoban *et al.* (1993a,b) derived a methanol production rate of $6 \pm 1.2 \times 10^{28}$ s^{-1} on 8 December and $3 \pm 0.9 \times 10^{28}$ s^{-1} on 10 December, suggesting large day-to-day fluctuations. The agreement with the submillimetre observations is reasonably good.

The inferred methanol production rate corresponds to an abundance relative to water of approximately 4%. I.R. observations between 8 and 12 November give CH_3OH production rates between 1.6 and 5.6×10^{28} s^{-1} (Davies *et al.*, 1993; Hoban *et al.*, 1993a,b) and CH_3OH abundances between 5 and 20%. The observations performed on 21 November at IRAM imply a CH_3OH production rate of 2.5×10^{28} s^{-1} and an abundance of 8% (Despois *et al.*, 1994). It is at present premature to conclude that there are significant time variations for the abundance of methanol relative to water because: (1) the water production rate was observed to be highly variable (A'Hearn *et al.*, 1992; Feldman *et al.*, 1993; Bockelée-Morvan *et al.*, 1994a); (2) the above abundances are based on isotropic coma models, while the actual coma was observed to be strongly asymmetric.

3.2. *HCN*

The J (4–3) rotational line of HCN at 354.5055 GHz was detected with a signal-to-noise ratio close to 100. As is shown in Fig. 2, the peak antenna temperature reached 2.5 K. To our knowledge, this is the strongest radio signal ever recorded from a comet, both in T_A^* and signal-to-noise ratio. Such a high signal-to-noise ratio will permit a detailed study of the line shape.

The HCN J(4–3) transition has six hyperfine components at 1.977 (F3–3), 0.367 (F3–4), 0.046 (F5–4), -0.111 (F3–2) and -1.610 (F4–4) MHz apart the F(4–3) component at 354.5055 GHz (as derived from Nguyen-Van-Thanh and Rossi, 1993). Assuming statistical-weight ratios, their intensities relative to the F(4–3) component are expected to be 0.067 (F3–3), 0.001 (F3–4), 1.304 (F5–4), 0.762 (F3–2) and 0.067 (F4–4). Since the three main lines contain 95% of the total intensity and are within 0.11 MHz of the average frequency, the observed line shape should primarily reflect the outflow morphology of the coma.

The shape of this line is particularly interesting due to its strong asymmetric aspect with a peak intensity at 0.8 km s^{-1} towards the blue and a mean velocity centre of -0.25 km s^{-1} with respect to the rest velocity. A similar shape is observed for the strongest 338 GHz lines of methanol. The various radio molecular lines observed with the Nançay, IRAM 30-m and CSO telescopes show a similar aspect (Colom *et al.*, 1993; Bockelée-Morvan *et al.*, 1994a; Despois *et al.*, 1994; Schloerb *et al.*, 1993). We interpret the asymmetric line shape of comet P/Swift–Tuttle as strong anisotropic outgassing towards the Sun. This result has to be correlated with the morphology of the dust in the inner coma which shows the presence of a strong helicoidal jet directed towards the Earth and encompassing almost 50% of the total observed flux (Yoshida *et al.*, 1993; Jorda *et al.*, 1994).

In contrast to methanol, the derivation of the HCN abundance from the observed line intensity can be expected to be more model dependent, since it relies on the assumed rotational temperature. There is *a priori* no reason to assume the methanol rotational temperature of 45 K which is characteristic of an out-of-equilibrium population distribution. Indeed, the distances at which breakdown of thermal equilibrium occurs in the HCN and CH_3OH coma are expected to be different due to different radiative lifetimes and collision rates. In order to compute the HCN production rate, we used the excitation model of Crovisier (1987) and assumed the parameters $\sigma_{coll} = 10^{-13}$ cm^2 and $T_{kin} = 80$ K which provide a good fit to the CH_3OH data. We derive an HCN production rate of $1.330 \pm 0.014 \times 10^{27}$ s^{-1}. Calculations with parameters (T_{kin}, σ_{coll}) in the range (30 K, 10^{-14} cm^2)–(100 K, 5×10^{-13} cm^2) give production rates within 30% of the above value. This results in an HCN abundance relative to water of 0.3%, in rough agreement with the abundance deduced from the observations of the 89 GHz line at IRAM of 21 November (Despois *et al.*, 1994).

3.3. *H_2CO*

The 5_{15}–4_{14} H_2CO line at 351.769 GHz was detected with a signal to noise of 18 (Table 2). As shown in Fig. 3, this line resembles, in shape, the HCN line, but slight differences seem to be present. These differences may indicate differences in the density distribution. As suggested by Schloerb and Ge (1992b), this could be an additional proof for the presence of a distributed source of formaldehyde in the coma (Meier *et al.*, 1993).

The fact that H_2CO could be produced from an extended source poses an supplementary problem for the derivation of the H_2CO production rate, in addition to those linked to the modelling of excitation conditions. In order to convert the observed line area into an H_2CO production rate, we have thus considered various density distributions. We present here results obtained with the excitation model of Bockelée-Morvan and Crovisier (1992). They are found to be only slightly dependent on the chosen collisional cross-section and kinetic temperature. The following values correspond to calculations performed with $\sigma_{coll} = 10^{-13}$ cm^2 and $T_{kin} = 80$K. The inferred H_2CO column density within the instrumental beam is approximately 7×10^{12} cm^{-2}. With the assumption of direct release from the nucleus, the derived H_2CO production rate is $4.9 \pm 0.3 \times 10^{27}$ s^{-1}, corresponding to an abundance of 1% with respect to water. This value can be interpreted as an upper limit for the formaldehyde production from the nucleus if, indeed, formaldehyde does not come solely from the nucleus. With the assumption of a distributed source with 3000 km scale length, which mimics the strength of the extended source in comet P/Halley (Meier *et al.*, 1993), the inferred production rate is not so different: 5.6×10^{27} s^{-1}. However, the H_2CO production rate reaches 8.6×10^{27} s^{-1} (1.7%), when a scalelength of 10,000 km is assumed.

4. Conclusion

We observed comet P/Swift–Tuttle 1992 XXVIII with the JCMT on 7 and 8 December 1992. These observations led to the detection of HCN, H_2CO and CH_3OH and demonstrated that submillimetre spectroscopy is a powerful tool for observing minor species of the cometary atmospheres and for studying the physical state of the coma. The relative intensities of the CH_3OH lines provided a critical test of the excitation models presently available. Strong constraints may be also expected from the comparison of these observations to those acquired at other frequencies with other millimetre and submillimetre telescopes (Despois *et al.* 1994; Schloerb *et al.*, 1993; Wootten *et al.*, 1994).

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Appendix

Frequency calibration for cometary radio observations is crucial, due to the narrowness of the lines and to the importance of line shapes for kinematical studies. The observation of galactic sources is of little help, due to their large line widths. The frequency calibration of an AOS-type spectrometer may slightly vary with time and as adjustments are made to the optical alignment. No calibration comb was available for the observations reported here, but fortunately we observed several cometary lines, covering both sidebands, which allowed us to calibrate the frequency scale using the observed data. A plot of the frequency offsets of the 338 GHz CH_3OH line peaks as a function of channel number showed a linear increase of 8.15×10^{-4} MHz per channel, corresponding to 1.67 MHz over the full 500 MHz passband, with a zero order term, or frequency offset between observed and expected line frequencies, of approximately 1 MHz at the centre of the band. The slope allowed us to derive the true channel spacing. A comparison of lines observed in the upper and lower sidebands then showed that their line centre frequencies differed by 0.24 MHz, which implies a further constant frequency correction of 0.12 MHz. This final calibration brings all lines in both sidebands into agreement with an error of a fraction of a channel width (0.25 MHz). The 1 MHz (0.9 km s^{-1}) zero-order term thus appears to be mainly of cometary origin. Indeed, the various cometary lines observed in comet P/Swift–Tuttle with other radio telescopes showed a similar offset for their peak intensity (cf. Sect. 3.2).