Observations of the $J = 4 \rightarrow 3$ transition of HCO$^+$ in OMC1, GL 961, Mon R2 and NGC 2071

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Received 1981 November 2; in original form 1981 September 25

Summary. We have observed the HCO$^+ J = 4 \rightarrow 3$ transition in OMC1 and three other galactic sources which have self-reversed CO profiles. None of the sources show self-absorption in this line and, in NGC 2071 and Mon R2, the line wings, seen in CO and HCO$^+ 1 \rightarrow 0$, have disappeared. Minimum masses between 200 and $1200 M_\odot$ are derived for the high-density cores; these lower limits will only be reduced significantly if HCO$^+$ is much more abundant than has previously been thought. A new compact, optically thin source is postulated in OMC1. We find a rest frequency at $356.7344 \pm 0.0005$ GHz for HCO$^+ 4 \rightarrow 3$ transition and values of $44.594 440 \pm 0.000 014$ GHz and $82.0 \pm 2.4$ kHz for the molecular constants $B_0$ and $D_0$.

1 Introduction

The $J = 1 \rightarrow 0$ transition of HCO$^+$ has recently been observed to be self-absorbed in a number of sources for which the CO transitions are also self-absorbed (Loren & Wootten 1980). As for any other molecule, observations of higher transitions are necessary if the excitation is to be understood. The $J = 2 \rightarrow 1$ transition is not accessible to ground-based telescopes because of atmospheric water-vapour absorption; Huggins et al. (1979) have observed the $J = 3 \rightarrow 2$ transition in Orion and Erickson et al. (1980) have reported the detection of this transition in 27 sources but have so far published only observations of Orion. We report here what we believe to be the first observations of the $J = 4 \rightarrow 3$ transition of HCO$^+$ at 357 GHz in four galactic sources; we use these observations to derive new values for the molecular constants $B_0$ and $D_0$ and to place constraints on the density of material producing the high-velocity wings and in the compact source cores.

2 Observations

The observations were made over a period of about 3 hr on 1981 January 16, using the indium antimonide hot-electron mixer receiver of the 3.8-m UK Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. The data-taking and observing techniques were similar to those described by White, Phillips & Watt (1981); typical integration times, both on and off the source, were 3 min, three or four pairs of frequency scans being averaged to produce the
Table 1. Sources observed and their line parameters.

<table>
<thead>
<tr>
<th>Source</th>
<th>Position RA (1950.0)</th>
<th>Dec.</th>
<th>$v_{lsr}^*$ (HCO+ 4 → 3 km s$^{-1}$)</th>
<th>$v_{lsr}$ (13CO 1 → 0 km s$^{-1}$)</th>
<th>$T_A^*$ (peak) (K)</th>
<th>$\Delta v$ (FWHM) (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMC1 (K–L)</td>
<td>5$^h$ 32$^m$ 47$^s$</td>
<td>–5° 23' 50''</td>
<td>–†</td>
<td>8.7</td>
<td>9.2</td>
<td>9.5†</td>
</tr>
<tr>
<td>NGC 2071</td>
<td>5 44 30 00</td>
<td>20 17</td>
<td>9.8</td>
<td>9.8‡</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Mon R2</td>
<td>6 05 20</td>
<td>–06 22 30</td>
<td>10.6</td>
<td>10.1‡</td>
<td>3.8</td>
<td>6.9</td>
</tr>
<tr>
<td>GL 961</td>
<td>6 31 59</td>
<td>04 15 07</td>
<td>12.8</td>
<td>12.8‡</td>
<td>3.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* Based on $f(4 → 3) = 356.7344$ GHz.
† See text for additional notes.
‡ Loren et al. (1981).

final spectra. The system noise temperature was ~ 1800 K (DSB) and the resulting spectra are limited principally by signal/noise considerations. The telescope was pointed by offsetting from bright stars and random errors probably amount to < 4 arcsec. There may, however, be a systematic offset of up to 20 arcsec due to the uncertainty in our determination of the angle between the optical and radio axes.

The sources observed are listed in Table 1 and the resulting spectra are shown in Fig. 1. Intensities are given in terms of $T_A^*$, the (Rayleigh–Jeans) antenna temperature defined as

![Figure 1 (a)](image1.png)

Figure 1. (a) Spectra obtained for the four source positions listed in Table 1. All spectra were obtained using a 0.9 km s$^{-1}$ resolution bandwidth. The spectra of NGC 2071, Mon R2 and GL 961 have been Hanning-smoothed to an effective resolution of 1.7 km s$^{-1}$. A linear baseline corresponding to the plateau component has been removed from the Orion spectrum. (b) The Orion spectrum, Hanning-smoothed to an effective resolution of 1.7 km s$^{-1}$. Shown dotted is the least-squares best fit of two component Gaussian profiles. The parameters of the Gaussian components are: (i) $T_{max}$ 7.8 K, $\Delta v$ (FWHM) 4.2 km s$^{-1}$ at $v_{lsr}$ 9.1 km s$^{-1}$ and (ii) $T_{max}$ 4.2 K, $\Delta v$ 2.6 km s$^{-1}$ at $v_{lsr}$ 12.9 km s$^{-1}$.
by Ulich & Haas (1976), i.e. the observed intensity in temperature units corrected only for
telescope and atmospheric losses. The relative contribution of telescope and atmospheric
attenuation was determined by sky-dipping; for the period of observation the zenith
temperature was \( \sim 50 \) K. Correction for sky attenuation was made assuming a secant law and
an atmospheric temperature of 270 K. The beam pattern was found from scans across
Jupiter. For an assumed disc brightness temperature of 150 K we deduce an aperture
efficiency of 43 per cent and a beamwidth of 59 arcsec (FWHM). We estimate a beam
efficiency of 70 per cent.

3 The HCO\(^+\) (4 \(\rightarrow\) 3) line frequency

The sources were observed using an assumed line frequency of 356.7332 GHz, derived from
the rotational constants given by Huggins et al. (1979) and values of \( v_{br} \) deduced from \(^{13}\)CO
data. We found a consistent offset to lower velocity in all the sources except Orion, by an
average of \( \sim 1.0 \) km s\(^{-1}\). We have used the \( J=1 \rightarrow 0 \) frequency of 89.188 523 GHz (Lovas,
Snyder & Johnson 1979) and determined a new rest frequency of 356.7344 GHz for the
\( J=4 \rightarrow 3 \) transition and hence values for \( B_0 \) and \( D_0 \) of 44.594 440 \( \pm 0.000 014 \) GHz and
82.0 \( \pm 2.4 \) kHz (in good agreement with the values recently determined in a laboratory
experiment by Bogey, Demuyck & Destombes (1981)). Our value for \( D_0 \) is lower than the
87.9 \( \pm 4.8 \) kHz of Huggins et al., but not significantly so, and is not so different from that of
the isoelectronic HCN value (\( D_0 = 87.24 \) kHz) as to make it doubtful. Velocities in this paper
have been calculated using a rest frequency of 356.7344 GHz.

4 Individual sources

4.1 OMC1

Previous single-dish observations of HCO\(^+\) in this source are summarized in Table 2. The fine
structure in HCO\(^+\) has also been mapped in aperture-synthesis observations by Welch et al.

Table 2. Summary of single-dish observations of HCO\(^+\) in OMC1.

<table>
<thead>
<tr>
<th>Transition</th>
<th>( T_A^* ) (K)</th>
<th>Beamwidth (FWHM) (arcmin)</th>
<th>Linewidth (FWHM) (km s(^{-1}))</th>
<th>Resolution (km s(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (\rightarrow) 0</td>
<td>10.1</td>
<td>1.25</td>
<td>4.2</td>
<td>{0.8}</td>
<td>1</td>
</tr>
<tr>
<td>3 (\rightarrow) 2</td>
<td>12(\dagger)</td>
<td>0.8(\ddagger)</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3 (\rightarrow) 2</td>
<td>12.5</td>
<td>1.1</td>
<td>5</td>
<td>1.1</td>
<td>3</td>
</tr>
<tr>
<td>4 (\rightarrow) 3</td>
<td>8.6</td>
<td>1.0</td>
<td>8.5</td>
<td>1.7</td>
<td>4</td>
</tr>
</tbody>
</table>

* As defined by Ulich & Haas (1976).
\(\dagger\) Huggins et al. do not make it clear whether this value has been corrected for
beam efficiency or not. Erickson et al. (1980) imply that it has, in which case the
value should read 12 \( \eta_B \).
\(\ddagger\) The theoretical beamwidth.

References
4. This paper.

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It is clear that there is a discrepancy between the linewidth measured by Turner & Thaddeus (1975) and Erickson et al. (1980), and those measured by Huggins et al. (1979) and the present authors. In Fig. 1(b) we show our spectrum of OMC1, Hanning-smoothed to an effective resolution of 1.7 km s\(^{-1}\) and, underneath it, a least-squares fit (to the unsmoothed data) in terms of two Gaussian components. Compared with the \(J=1 \rightarrow 0\) spectrum there is an additional feature with the higher \(v_{\text{lsr}}\) of \(\approx 13\) km s\(^{-1}\), consistent with a compact, hot, optically thin component. In the limit of hot, dense, optically thin gas, the optical depth, and hence brightness temperature, for rotational transitions \(J \rightarrow J-1\) of linear molecules, scales as \(J^2\) (Goldsmith 1972). Turner & Thaddeus (1975) and Welch et al. (1981) would then have failed to detect this component because of its low brightness in the \(1 \rightarrow 0\) transition. Comparison with the \(J = 3 \rightarrow 2\) results of Erickson et al. (1980) and Huggins et al. (1979) is complicated by their mutual inconsistency, but there is some evidence for broadening in the spectrum given by the latter which could be caused by such a component. (This could also contribute to the small discrepancy between our determination of the rotational constants and theirs.)

The nature of this additional compact emission feature is not clear but it could be related to the 12.6 km s\(^{-1}\) feature observed in CO \(1 \rightarrow 0\) to the NW of the BN object by Loren (1979). From his fig. 3b this would appear to be a continuation of a partial ring of high-velocity gas which he interprets as emission due to the shock associated with the \(H^+\) ionization front. This shock could provide the required excitation for this component as well as enhancing the relative HCO\(^+\)/CO abundance (Dickinson et al. 1980).

### 4.2 GL 961

This source, the SE of the Rosette nebula, is one of only two sources (the other being NGC 2071) for which the self-absorbed CO emission appears to indicate expansion (Loren et al. 1981). The only previous observations of HCO\(^+\) in GL 961 are those by Stark (1981) who failed to see any self-absorption in the \(1 \rightarrow 0\) transition. The narrow linewidth observed in the \(4 \rightarrow 3\) transitions of HCO\(^+\) is probably indicative of a low average density of molecular material in the source. This would at the same time explain the low excitation-temperature of the absorbing CO seen in the \(2 \rightarrow 1\) and \(3 \rightarrow 2\) transitions and the lack of detectable HCO\(^+\) \(J=1 \rightarrow 0\) self-reversal.

### 4.3 NGC 2071

This source lies in a reflection nebula in the Lynds 1630 dark cloud complex. It is observed to be self-absorbed in the CO \(1 \rightarrow 0\) and \(2 \rightarrow 1\) transitions (Loren et al. 1981; Phillips et al. 1981) and in the \(1 \rightarrow 0\) transition of HCO\(^+\) (Loren & Wootten 1980). As in GL 961, the velocity shift between the \(^{12}\)CO self-absorption dip and the \(^{13}\)CO emission peak appears to indicate that the source is expanding.

Our \(J = 4 \rightarrow 3\) spectrum of HCO\(^+\) in this source differs greatly from the \(1 \rightarrow 0\) spectrum. Not only is there no indication of high-velocity emission in the line wings, but also the self-absorption has disappeared. The peak antenna temperature is \(\approx 2.3\) times that observed in the \(1 \rightarrow 0\) transition. The form of the \(4 \rightarrow 3\) spectrum is generally consistent with that predicted by Loren & Wootten (for a source with a \(v \propto \tau^{1/2}\) velocity law), although any line asymmetry is obscured by the noise and it is not possible to distinguish between expansion or collapse. However, we note that such a conclusion is valid only if the source is well resolved.

Since the aperture and beam efficiencies of the NRAO 11-m telescope at 90 GHz and the UKIRT at 360 GHz are similar, the expected ratio of antenna temperatures for an unresolved
source is equal to the ratio of source brightness weighted by the respective forward gains of the telescope (1.91). The data are thus also consistent with the source being unresolved and having comparable brightness temperatures and sizes in the $1\rightarrow 0$ and $4\rightarrow 3$ transitions.

4.4 MON R2

As noted, the self-absorption in the CO lines and in the HCO$^+$ $1\rightarrow 0$ transition appear to indicate collapse (Loren & Wootten 1980). As for NGC 2071, the line wings and self-absorption have disappeared in the $4\rightarrow 3$ transition but the peak $T_A^*$ is only slightly enhanced relative to the $1\rightarrow 0$ line (by a factor of $\sim 1.1$ compared with 2.3 for NGC 2071). The large negative feature at $\sim 4$ km s$^{-1}$ may be due to emission in the reference beam at $+5$ m in RA, although this is not apparent in CO maps of the region. The line shape is again in qualitative agreement with that predicted by Loren & Wootten for a source having $v \propto r^{-1/2}$ collapse and $r^{-2}$ density variation. Although only marginally significant in relation to the noise, the sense of the observed asymmetry would imply expansion rather than collapse.

5 Discussion

Previous observations of molecular cloud cores in the three lowest transitions of CO have suggested that in many cases the data are consistent with a model in which the source is undergoing overall collapse (or, in a few cases, expansion) (Snell & Loren 1977; Loren et al. 1981) with higher velocity dispersion being seen toward the centre of the cloud. The 'broad wing' emission is generally assumed to be associated with the compact core and its embedded IR source. The present observations have revealed two clouds (NGC 2071 and Mon R2) for which the lower-excitation HCO$^+$ $1\rightarrow 0$ transition has just such a 'classical' self-absorbed profile and which have undetectable $J=4\rightarrow 3$ emission in the broad wings. One interpretation of these results is that the observed profiles near the centre of the self-reversed sources consist of emission from two distinct components—a relatively low density high-velocity stream and a higher density low-velocity source. We now consider further implications of these results.

5.1 THE HIGH-VELOCITY GAS

Assuming that this material is associated with the high-excitation core, and noting the larger beamwidth of the $1\rightarrow 0$ measurements, we conclude that our failure to detect the line wings in the $4\rightarrow 3$ transition is due to insufficient excitation at that frequency. We believe that the most likely cause for this is that the high-velocity source has a relatively low density. A value of $n_{H_2}$ in the range $3 \times 10^4$—$1 \times 10^6$ cm$^{-3}$ would be sufficient just to excite the $1\rightarrow 0$ transition but give negligible excitation of the $J=4\rightarrow 3$ transition. Lower density limits will pertain if the $1\rightarrow 0$ transition has high optical depth.

5.2 THE HIGH-DENSITY MATERIAL

The observed intensity of the HCO$^+$ $4\rightarrow 3$ line can be used to place constraints on the mass of high-density gas. The minimum total number of HCO$^+$ molecules in the $J=4$ state is given by

$$N_4 = \int \frac{\Delta v}{v} n_4 \cdot dv = \frac{4\pi R_0^2 S_\nu}{A_{4,3} \Delta v \cdot h \nu}$$
where $\Delta \nu_e$ is the equivalent linewidth, $R_0$ the source distance, $S_r$ the observed peak flux density in the line, and $A_{1,4}$ the appropriate Einstein rate coefficient. By assuming that the HCO$^+$ $J=4$ level is approximately thermalized at temperature $T_k \sim 40$ K and that the relative abundance HCO$^+$/H$_2$ is $\sim 3 \times 10^{-11}$, a minimum mass for the high density gas is obtained. If the populations are in LTE the number of molecules in the $J=4$ level is approximately maximized at the assumed temperature of 40 K, so that any other temperature will lead to higher mass estimates. Subthermal excitation of the higher levels should also cause an under-estimation of the mass.

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance</th>
<th>$M_{\text{min}}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL 961</td>
<td>1600</td>
<td>1170</td>
<td>1</td>
</tr>
<tr>
<td>NGC 2071</td>
<td>500</td>
<td>230</td>
<td>2</td>
</tr>
<tr>
<td>Mon R2</td>
<td>850</td>
<td>1070</td>
<td>3</td>
</tr>
</tbody>
</table>

* Assuming $T_k = 40$ K, $[\text{HCO}^+]/[\text{H}_2] = 3 \times 10^{-11}$.

References

The results of these calculations are given in Table 3 for NGC 2071 and Mon R2 (for which the integrated intensity is well determined), and also for GL 961 (where the noise is somewhat higher). The mass estimates depend directly on the assumed HCO$^+$/H$_2$ ratio. Wootten et al. (1978) find a value of $1.3 \times 10^{-11}$ as an average value in warm clouds, whereas Loren & Wootten (1980) found it necessary to use a ratio of $3 \times 10^{-11}$ in order to model the 1→0 self-absorption successfully in a hypothetical source. We have adopted the latter conservative value of $3 \times 10^{-11}$ with the caveat that, if the abundance quoted by Wootten et al. (1978) is correct, the derived masses may be up to a factor of 2 higher. Our minimum mass values appear high even if it is considered that at least one high-luminosity star is associated with each source (assuming a star-forming efficiency of $\sim 30$ per cent, and that the star has not yet had time to blow out the placental material).

These estimates will be reduced only if the HCO$^+$ relative abundance is significantly greater than the value assumed. It is not clear that the large amounts of HCO$^+$ which we would then be seeing could be formed by the standard process of cosmic-ray ionization in such dense clouds (e.g. Watson 1976), particularly in the presence of possible mass outflow, so it might then be necessary to invoke some new mechanism for the production of this species.

Acknowledgments
We gratefully acknowledge the staff of the UK Infrared telescope for their assistance during the period of the observations. We also thank A. T. Nicol and D. W. J. Bly for their technical support both before and during the observing trip. R.P. is grateful to the Royal Commission for the Exhibition of 1851 for a research Fellowship.
References


