BIMA ARRAY DETECTIONS OF HCN IN COMETS LINEAR (C/2002 T7) AND NEAT (C/2001 Q4)

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ABSTRACT

We present interferometric detections of HCN in comets LINEAR (C/2002 T7) and NEAT (C/2001 Q4) with the Berkeley-Illinois-Maryland Association (BIMA) Array in its D-configuration cross-correlation mode. We detected the HCN $J = 1-0$ emission line in both comets. With a $25''.4 \times 20''.3$ synthesized beam around Comet LINEAR, we found a total beam averaged HCN column density (assuming a rotation temperature of 146 K) of $< N_T > = 2.1(11) \times 10^{13}$ cm^{-2}, and a HCN production rate of Q(HCN)=2.8(15)$\times 10^{27}$ s^{-1}. With a $21''.3 \times 17''.5$ synthesized beam around Comet NEAT, we found a total beam averaged HCN column density (assuming a rotation temperature of 107 K) of $< N_T > =$

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$5.7(30)\times 10^{12}$ cm^{-2}, and a HCN production rate of Q(HCN)=$8.3(44)\times 10^{26}$ s^{-1} giving a production rate of HCN relative to H_2O of ~0.09(5)%. The production rates relative to H_2O and spatial extent of HCN are similar to previous comet observations.

Subject headings: comets: individual (LINEAR (C/2002 T7)) - comets: individual (NEAT (C/2001 Q4)) - molecular processes - techniques: interferometric - radio lines: solar system

1. INTRODUCTION

HCN has been extensively studied around several comets including Comet P/Halley (Despois et al. 1986), Comet Hyakutake (C/1996 B2) (e.g., Matthews et al. 1996a; Matthews, Jewitt, & Irvine 1996b; Womack et al. 1996; Senay, Matthews, & Jewitt 1996; Mumma et al. 1996; Lis et al. 1997), Comet Hale-Bopp (C/1995 O1) (e.g., Fitzsimmons et al. 1995; Wright et al 1998; Hirota et al. 1999; Magee-Sauer et al. 1999; Ziurys et al. 1999; Veal et al. 2000; Snyder et al. 2001; Woodney et al. 2002) and Comet LINEAR (C/1999 S4) (Bockelée-Morvan et al. 2001; Hogerheijde et al. 2004). Veal et al. (2000) made some of the first interferometric observations of HCN in Comet Hale-Bopp. From the distribution and temporal behavior of the HCN emission, they were able to make very accurate calculations of the HCN production rate as well as modeling its distribution in the coma using a spherical Haser model (Haser 1957). The deviations from the Haser parent model were explained by the existence of jets releasing HCN gas, a conclusion directly supported by high spatial resolution interferometric imaging of Comet Hale-Bopp by Blake et al. (1999). Snyder et al. (2001) followed up the observations of Veal et al. (2000) and found the measured HCN scale length to be very similar to the theoretical predictions of Huebner, Keady, & Lyon (1992) and Crovisier (1994). Many of the conclusions found at mm-wavelengths around Comet Hale-Bopp could only have been determined by interferometry.

In the Spring of 2004, we were awarded a rare opportunity to observe two comets passing into the inner solar system and within ~0.3 AU of the Earth. Comet LINEAR (C/2002 T7) reached perigee on 2004 May 19, coming within 0.27 AU of the Earth, while Comet NEAT (C/2001 Q4) reached perigee on 2004 May 7, coming within 0.32 AU of the Earth. Both comets were identified as being dynamically new; such comets reach a peak of strong activity as they approach perihelion. However, the activity drops significantly as they start to head back out toward the outer solar system. So timing was extremely important in order to observe both comets between the time they reached perihelion and perigee.

This Letter describes the results of an effort to observe HCN in both Comets LINEAR and NEAT, with the Berkeley-Illinois-Maryland Association (BIMA) Array[1] near Hat Creek, California (§2). We present interferometric detections of HCN in both comets and measured the total beam averaged HCN column density and production rate. Thus, we were able to compare the abundance and distribution of HCN with other comets as well as determine the physical structure of the coma and the source of HCN.

2. OBSERVATIONS

We used the BIMA Array at Hat Creek, California (122°28′8″.4 West, 40°49′2″.28 North; altitude 1333 m) in its D-configuration (baselines from ∼6m to ∼35m) cross-correlation mode to observe HCN in Comets LINEAR (C/2002 T7) and NEAT (C/2001 Q4) during their 2004 apparitions.

The HCN observations of Comet LINEAR, using JPL reference orbit 69, were taken 2004 May 11 toward the topocentric coordinates α=01^{h}15^{m}59.^{s}06; δ=−07°39′16.5″ [J2000.0][2] at the beginning of our observations, and moved to α=01^{h}18^{m}20.^{s}56; δ=−07°52′33.9″ [J2000.0] by the end of our observations. The comet was at a heliocentric distance of 0.73 AU and a geocentric distance of 0.44 AU. The spectral window containing the HCN hyperfine components had a bandwidth of 50 MHz and was divided into 128 channels giving a spectral resolution of 0.39 MHz (1.321 km s^{-1}) per channel. W3(OH) was used as the flux density calibrator for this observation. The quasar 0108+015 was used to calibrate the antenna based gains. The absolute amplitude calibration is believed to be accurate to within ∼20%.

The HCN observations of Comet NEAT, using JPL reference orbit 123, were taken 2004 May 23 toward the topocentric coordinates α=09^{h}13^{m}54.^{s}67; δ=36°46′30.7″ [J2000.0] at the beginning of our observations, and moved to α=09^{h}15^{m}23.^{s}16; δ=37°18′34.9″ [J2000.0] by the end of our observations. The comet was at a heliocentric distance of 0.97 AU and a geocentric distance of 0.61 AU. The spectral resolution was the same as toward Comet LINEAR. Mars was used as the flux density calibrator and 0927+390 was used to calibrate the antenna based gains. The data were combined and imaged using the MIRIAD software package (Sault, Teuben, & Wright 1995). Table 1 lists the HCN molecular line parameters near 88.6 GHz. All the HCN spectroscopic constants were taken from Maki (1974).

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[1]Operated by the University of California, Berkeley, the University of Illinois, and the University of Maryland with support from the National Science Foundation.

[2]We believe the positional accuracy to be good to a few arcseconds for our observations, which is insignificant given the size of our FWHM synthesized beams.

3. RESULTS

Figure 1(a-c) shows our map and spectra of HCN around Comet LINEAR (C/2002 T7). Figure 1a shows the map of the $J = 1-0, F = 2-1$ transition of HCN in 1 σ contours, starting at 2 σ. The synthesized beam of $25''.4 \times 20''.3$ is shown at the bottom left of the map. The coordinates are given in offset arcseconds centered on the comet nucleus. The line segment in the image shows the projection of the direction toward the sun. The origin of the line segment is anchored at the predicted position of the comet nucleus. We note that the peak intensity of the HCN emission is offset from the predicted position of the nucleus, but given the size of our synthesized beam and our signal-to-noise, we do not consider the offset to be significant. Figure 1b shows the cross-correlation spectrum of this transition near 88.6 GHz. The dashed line corresponds to the rest frequency of the $J = 1-0, F = 2-1$ line for a cometocentric rest velocity of 0 km s^{-1}. The 1 σ rms noise level is seen at the left of the panel. Figure 1c shows the cross-correlation spectrum (Hanning smoothed over three channels) of this transition.

Figure 1(d-f) shows our map and spectra of HCN around Comet NEAT (C/2001 Q4). Figure 1d shows the map of the $J = 1-0, F = 2-1$ transition of HCN in 1 σ contours, starting at 2 σ. The synthesized beam of $21''.3 \times 17''.5$ is shown at the bottom left of the map. Figure 1e shows the cross-correlation spectrum of this transition near 88.6 GHz. The dashed line is similar to Figure 1b. Figure 1f shows the cross-correlation spectrum (Hanning smoothed over three channels) of this transition.

4. COLUMN DENSITIES AND PRODUCTION RATES

In the innermost coma, collisions between cold cometary species dominate the rotational population of the gas, but in the less dense outer coma, the solar wind and cometary ions are mixed and the population can also be determined by fluorescence driven by solar radiation. Fluorescence effects could allow LTE to be maintained at a lower density than required in optically thin cases (e.g., Crovisier et al. 1984; Bockelée-Morvan et al. 1987). However, as discussed by Snyder et al. (2001), our interferometric observations should be dominated by coma emission in the collisional regime and insensitive to fluorescence effects except those directly between us and the comet. For cross-correlation observations, $< N_T >$, the beam-averaged molecular column density, is

$$< N_T >= \frac{2.04 \; W_{\rm I} \; Z \; e^{E_{\rm u}/T_{\rm rot}}}{\theta_{\rm a}\theta_{\rm b} S \mu^2 \nu^3} \times \; 10^{20} \; {\rm cm}^{-2}. \quad (1)$$

In equation (1), $W_{\rm I} = \int I_\nu dv$ in Jy beam^{-1} km s^{-1}, and I_ν is the flux density per beam. Z is the rotational partition function, $\theta_{\rm a}$ and $\theta_{\rm b}$ are the FWHM synthesized beam dimensions in arcsec, S is the line strength, μ^2 the square of the dipole moment in Debye^2, and ν is the frequency in GHz.

The beam-averaged column densities from equation (1) can be used with a Haser model (Haser 1957) to find Q_p, the parent molecule production rate as described by Wright et al (1998) and Veal et al. (2000). For a photodissociation scale length λ_p, nuclear radius r_n, and constant radial outflow velocity v_0, the density as a function of r, $n_p(r)$, is given by Snyder et al. (2001):

$$n_p(r) = \frac{Q_p}{4\pi r^2 v_0} e^{-\frac{(r-r_n)}{\lambda_p}}. \tag{2}$$

For Comets LINEAR and NEAT, we will assume a nuclear radius of $r_n = 5$ km. We use a radial outflow velocity of $v_0 = 1.79$ km s^{-1} for Comet LINEAR and $v_0 = 1.59$ km s^{-1} for Comet NEAT, based on measurements from Howell, Lovell, & Schloerb (2004) and scaling relations given in Biver et al. (1999) and Fink & Combi (2004).

Consider a point on the line of sight that passes a projected distance, p, in the plane of the sky from the nucleus. For a given value of z, measured along the line of sight, this will correspond to a radial distance $r = \sqrt{(p^2 + z^2)}$ from the nucleus. The column density, N_p, is given by Snyder et al. (2001):

$$N_p(p) = \frac{Q_p}{4\pi v_0} e^{\frac{r_n}{\lambda_p}} \int_{-\infty}^{\infty} \frac{\exp\{-[(p^2+z^2)^{1/2}/\lambda_p]\}}{(p^2+z^2)} dz. \tag{3}$$

Finally, N_p from equation (3) may be averaged over the synthesized beam and equated to $< N_T >$, the beam-averaged molecular column density, in order to obtain Q_p, the parent molecule production rate from the Haser model.

In order to calculate the column densities we calculated a rotation temperature, based on heliocentric distance relations in Biver et al. (1999), of 146 K for Comet LINEAR and 107 K for Comet NEAT. From Figure 1b, we find an integrated line intensity of 0.83(44) Jy beam^{-1} km s^{-1} for the $J = 1-0, F = 2-1$ HCN line around Comet LINEAR. We find a total beam averaged HCN column density of N$_T$ = 2.1(11)× 10^{13} cm^{-2}. Similarly, from Figure 1e, we find an integrated line intensity of 0.22(11) Jy beam^{-1} km s^{-1} for the $J = 1-0, F = 2-1$ HCN line around Comet NEAT. We find a total beam averaged HCN column density of N$_T$ = 5.7(30)× 10^{12} cm^{-2}.

The Quiet Sun HCN photodissociation rate in the Solar UV field at $r_{hel} = 1$ AU is given by Huebner et al. (1992) as $\alpha(1\ \mathrm{AU}) = 1.3 \times 10^{-5}\ \mathrm{s}^{-1}$ and by Crovisier (1994) as $1.5 \times 10^{-5}\ \mathrm{s}^{-1}$. The expected accuracy is 10-20% (Crovisier 1994), so this is reasonable agreement. If we use an HCN scale length corresponding to $\alpha(1\ \mathrm{AU}) = 1.3 \times 10^{-5}\ \mathrm{s}^{-1}$ (equivalent to $\sim 1.0 \times 10^5$ km for Comet NEAT and $\sim 6.4 \times 10^4$ km for Comet LINEAR), we find that the May 11 interferometric data around Comet LINEAR give a production rate, Q(HCN), of $2.8(15) \times 10^{27}\ \mathrm{s}^{-1}$, and the May 23 data around Comet NEAT give a production rate of $8.3(44) \times 10^{26}\ \mathrm{s}^{-1}$. The only reported production rate for H_2O for either comet was by Lecacheux et al. (2004) around Comet NEAT. They measured $Q(H_2O) = 1.3 \times 10^{29}\ \mathrm{s}^{-1}$ at a heliocentric distance of $\sim$1.52 AU. By using the power law relations given in Biver et al. (1999) and Fink & Combi (2004), we adjusted this value to a heliocentric distance of 0.97 AU for our observations, giving $Q(H_2O) = 9.5 \times 10^{29}\ \mathrm{s}^{-1}$. Using this value we find the production rate of HCN relative to H_2O to be $\sim$0.09(5)% for Comet NEAT. Since rotation temperatures can very from comet to comet we also analyzed out data for a range of temperatures. Table 2 summarizes our results for temperatures of 50 K(which has been used by Bockelée-Morvan et al. (2001) for Comet LINEAR (C/1999 S4)), 107 K(calculated for the heliocentric distance of Comet NEAT), and 150 K(similar to that calculated for Comet LINEAR) for Comet NEAT. The first column gives the rotation temperature, the second gives the total column density, the third gives the HCN production rate, and the final column gives the HCN production rate relative to that of H_2O.

For Comet LINEAR, since no H_2O production rate has been published to date, we have estimated $Q(H_2O)$ from Q(HCN). Assuming a relative production rate of 0.17% (averaged from Comet Hyakutake (Lis et al. 1997) and Comet Hale-Bopp (Snyder et al. 2001)), we calculate a H_2O production rate of $\sim 1.7(9) \times 10^{30}\ \mathrm{s}^{-1}$, which is not unreasonable. Table 3 summarizes our results for Comet LINEAR for temperatures of 50 K(which has been used by Bockelée-Morvan et al. (2001) for Comet LINEAR (C/1999 S4)), 100 K(similar to that calculated for Comet NEAT), and 146 K(calculated for the heliocentric distance of Comet LINEAR). The first column gives the rotation temperature, the second gives the total column density, the third gives the HCN production rate, and the final column gives our calculated H_2O production rate, assuming the above relative rate.

The production rates of HCN around both comets are similar to the production rates seen around Comet LINEAR (C/1999 S4) (Bockelée-Morvan et al. 2001) and Comet Hale-Bopp (Snyder et al. 2001). Additionally, the relative production rate of HCN/H_2O in Comet NEAT (0.09(5)%) is also similar to those found in Comet Hale-Bopp (0.21-0.26%) (Snyder et al. 2001) and Hyakutake ($\sim$0.1%) (Lis et al. 1997). Our estimated H_2O production rate for Comet LINEAR ($1.7(9) \times 10^{30}\ \mathrm{s}^{-1}$) lies between the values for Comet LINEAR (C/1999 S4) ($\sim 10^{28}\ \mathrm{s}^{-1}$) (Bockelée-Morvan et al. 2001) and Comet Hale-Bopp ($\sim 10^{31}\ \mathrm{s}^{-1}$) (Snyder et al. 2001) and is in good agreement with the adjusted OH production rate (equivalent to that of H_2O) of $\sim 9.8\times10^{29}$ s^{-1}, calculated from Howell et al. (2004), Biver et al. (1999), and Fink & Combi (2004). Overall, the production rates are consistent with no significant HCN production or destruction, except photodissociation, in the inner coma region bounded by the synthesized FWHM beam.

We thank John Dickel for assisting with the observations. This work was partially funded by: NASA NAG5-4292, NAG5-4080, NAG5-8708, and NGT5-0083; NSF AST96-13998, AST96-13999, AST96-13716, AST96-15608, AST99-81363, AST02-28953; and the Universities of Illinois, Maryland, and California, Berkeley.

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This preprint was prepared with the AAS LaTeX macros v5.2.

Table 1. HCN Molecular Line Parameters

Quantum Numbers	Frequency (MHz)	E_u (K)	$< S_{i,j}\mu^2 >$ (Debye^2)
$J = 1 - 0, F = 1 - 1$	88,630.4157(10)	4.3	3.0
$J = 1 - 0, F = 2 - 1$	88,631.8473(10)	4.3	4.9
$J = 1 - 0, F = 0 - 1$	88,633.9360(10)	4.3	1.0

Table 2. HCN Column Densities and Production Rates For Comet NEAT

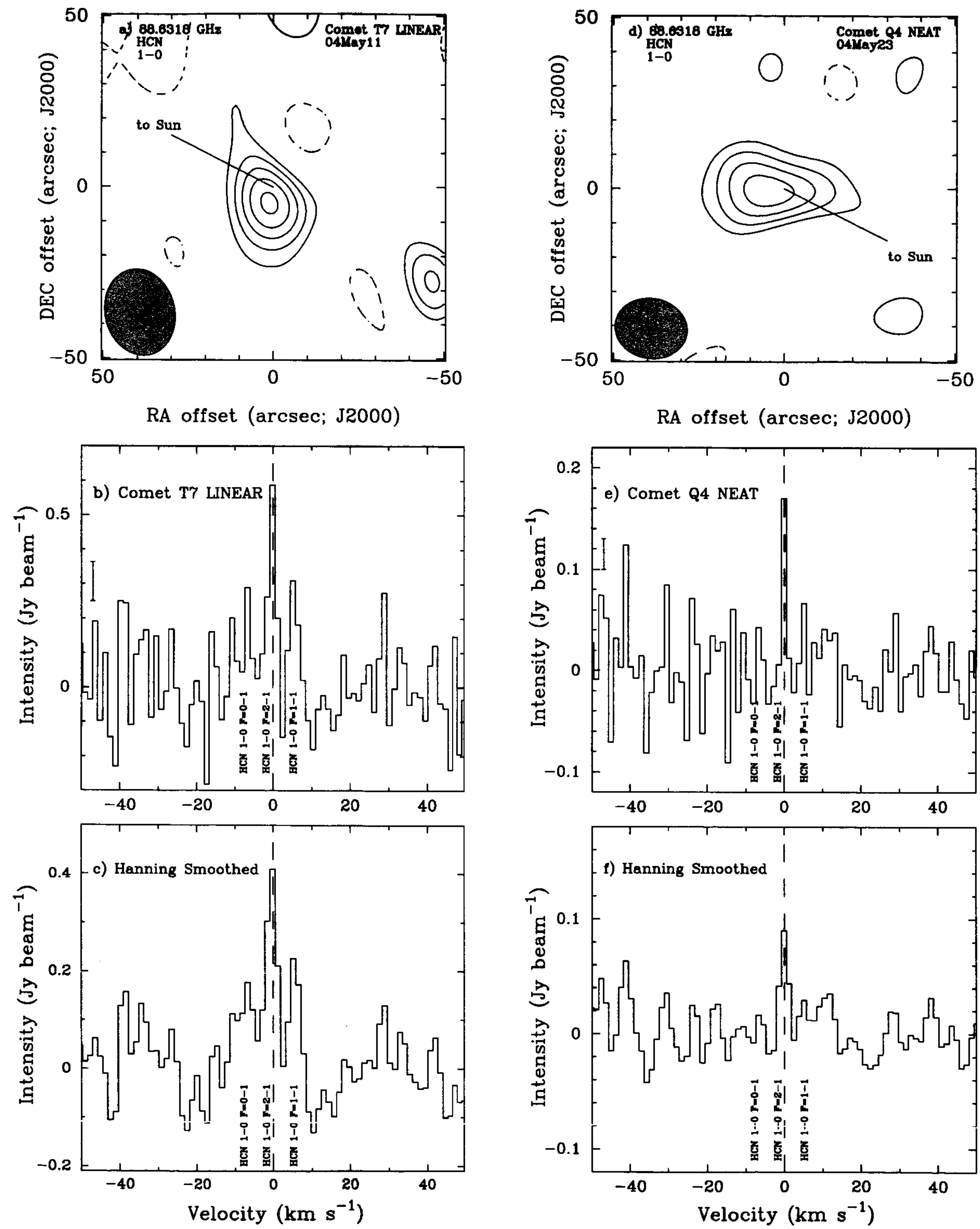
T_{rot} (K)	N_T (cm^{-1})	Q(HCN) (s^{-1})	$\frac{Q(HCN)}{Q(H_2O)}$
50	$2.8(15)\times10^{12}$	$4.1(22) \times 10^{26}$	$4.3(23) \times 10^{-4}$
107	$5.7(30)\times10^{12}$	$8.3(44) \times 10^{26}$	$8.7(46) \times 10^{-4}$
150	$7.8(42)\times10^{12}$	$1.2(6) \times 10^{27}$	$1.2(6) \times 10^{-3}$

Table 3. HCN Column Densities and Production Rates For Comet LINEAR

T_{rot} (K)	N_T (cm^{-1})	Q(HCN) (s^{-1})	Q(H_2O)[a] (s^{-1})
50	$7.4(4)\times10^{12}$	$1.0(5) \times 10^{27}$	$6.0(32) \times 10^{29}$
100	$1.4(8)\times10^{13}$	$2.0(10) \times 10^{27}$	$1.2(6) \times 10^{30}$
146	$2.1(11)\times10^{13}$	$2.8(15) \times 10^{27}$	$1.7(9) \times 10^{30}$

[a]Calculated from Q(HCN) assuming a ratio of 1.7×10^{-3}.

Fig. 1.— Comet LINEAR (C/2002 T7) and NEAT (C/2001 Q4) single field HCN images and spectra. (a) Comet T7 emission contours from the $J = 1 - 0, F = 2 - 1$ transition of HCN at 88.6318 GHz. Contours indicate the HCN emission near its peak centered at a cometocentric velocity of 0 km/s. The contour levels are -0.2, 0.2, 0.3, 0.4, 0.5 and 0.6 Jy/beam (1σ spacing). The peak is 0.63 Jy/beam. Image coordinates are arcseconds offsets relative to the predicted position of the nucleus. The synthesized beam of $25.41'' \times 20.34''$ is in the lower left and the line segment shows the solar direction. (b) HCN cross-correlation spectra. Abscissa is radial velocity relative to the comet nucleus. Ordinate is flux density per beam, I_ν, in Jy/beam; $\sigma \sim 0.113$ Jy/beam (indicated by the vertical bar at the left). The dashed line is centered on the rest frequency (88.6318 GHz).(c) HCN cross-correlation spectra (Hanning smoothed over 3 channels), labels the same as in (b). (d) Comet Q4 emission contours from the $J = 1 - 0, F = 2 - 1$ transition of HCN. Contours indicate the HCN emission near its peak centered at a cometocentric velocity of 0 km/s. The contour levels are -0.06, 0.06, 0.09, 0.12 and 0.15 Jy/beam (1σ spacing). The peak is 0.17 Jy/beam. Image coordinates are the same as in (a). The synthesized beam of $21.27'' \times 17.53''$ is in the lower left and the line segment shows the solar direction. (e) HCN cross-correlation spectra, abscissa and ordinate are the same as in (b); $\sigma \sim 0.03$ Jy/beam (indicated by the vertical bar at the left). The dashed line is centered on the rest frequency (88.6318 GHz). (f) HCN cross-correlation spectra (Hanning smoothed over 3 channels), abscissa and ordinate are the same as in (b).


a) 88.6318 GHz
HCN
1-0
Comet T7 LINEAR
04May11
to Sun
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
d) 88.6318 GHz
HCN
1-0
Comet Q4 NEAT
04May23
b) Comet T7 LINEAR
e) Comet Q4 NEAT
c) Hanning Smoothed
f) Hanning Smoothed
HCN 1-0 F=0-1
HCN 1-0 F=2-1
HCN 1-0 F=1-1
Intensity (Jy beam^{-1})
Velocity (km s^{-1})