A SEARCH FOR VARIABILITY IN THE HCN TO H_2CO RATIO IN COMET HALE–BOPP

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Abstract. We observed submillimeter lines of H_2CO and HCN in comet Hale–Bopp near perihelion. One of our goals was to search for short term variability. Our observations are suggestive, but not conclusive, of temporal and/or spatial changes in the coma's HCN/H_2CO abundance ratio of ∼25%. If due to spatial variability, the ratio on the sunward side of the coma is enhanced over other regions. If due to temporal variability, we find the bulk ratio in the coma changed in less than 16 hours.

Keywords: Comet, HCN, H_2CO, variability, submillimeter

1. Introduction

During the recent passages of bright comets Hyakutake and Hale–Bopp, millimeter/submillimeter wavelength observations have proven themselves to be a powerful tool in the remote sensing of comets, as evidenced by many of the reports in this volume. The abundance, velocity, and spatial distribution of various species have been studied. Our group made such observations of Hale–Bopp using the Heinrich Hertz Telescope at the Submillimeter Telescope Observatory in Arizona. The telescope is a 10 meter diameter antenna, at an altitude of 3178 meters (see Baars et al. (1998) for a complete description). For the observations discussed in this paper, our beam size was ∼22″, corresponding to 21,000 km at the comet. We used facility and PI receivers providing access to the ∼320 to ∼510 GHz range, and a Chirp Transform Spectrometer (CTS) providing 43 kHz resolution and a 178 MHz bandwidth. (The CTS is an analog Fourier Transform device. See Hartogh (1997) for details.) We used an observatory supplied Hale–Bopp ephemeris, but checked it against the JPL DE403 ephemeris made available on the internet by Don Yeomans and dated 4 March 1997. Ephemeris errors are expected to be less than 2″, which is small compared to other sources of pointing error (discussed later).

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We observed Hale–Bopp on three occasions, detecting the indicated species.

November 6–11, 1996:	CO(3-2) and CO(4-3).
March 25–31, 1997:	CO, HCN, H_2CO, CH_3OH, and CO+.
April 30–May 5, 1997:	CO, HCN, H_2CO, and HCO+.

An instrument description and analysis of our CO data is presented in Hartogh et al. (1999). The current paper focuses on measurements of the HCN to H_2CO ratio in March 1997. By discussing the relative abundance of these species, rather than absolute values, we remove many sources of error. We find a suggestion of variability at the 25% level over 27 hours of monitoring. We cannot confirm the variability, however, because a particular combination of receiver sideband instability and antenna pointing errors could mimic the effect we see. If real, the observed changes could be due to temporal variability in the coma, tied to the apparent $\sim$11.3 hour rotation period of the nucleus (Farnham, et al., 1997, and several reports in these Proceedings). In this scenario, different regions of the nucleus have different compositions, and as regions rotate in and out of sunlight there is a change in nucleus outgassing affecting the bulk composition of the coma. Our observations could also be explained by spatial variability in the coma – an enhanced ratio on the sunward side of the nucleus – coupled with an antenna pointing error. To explain this scenario, we would invoke differences between the dayside and nightside emission from the nucleus and/or radiative processes in the coma that enhance the HCN/H_2CO ratio on the sunward side. The nucleus itself, however, can be homogeneous in this interpretation.

2. Spectra and Integrated Line Areas

Figure 1a shows a full resolution CTS spectrum from 29 March 1997. The integration time was approximately 30 minutes. When observing the H_2CO line at 351.769 GHz in the lower sideband, we also see the HCN (4-3) line at 354.505 GHz in the upper sideband. The bottom axis is frequency, expressed as the equivalent Doppler velocity of the H_2CO line. (HCN appears near the 30 km/s channel, not because it actually has that velocity, but because its frequency is different.) Since the species are observed in different sidebands, their shapes are mirror images. H_2CO is in the correct orientation, with enhanced emission from gas approaching the observer (negative velocity). Figure 1b shows the two lines with their true Doppler velocity structure. There is a great deal of information in the detailed shape of these lines, but we defer that discussion to a future paper. For now, it is sufficient to note that HCN is more extended in the positive velocity direction and that, relative to the total line area, H_2CO has a stronger peak at negative velocities. Also, we find no significant variations in the shape of either line over the 27 hours we observed them.

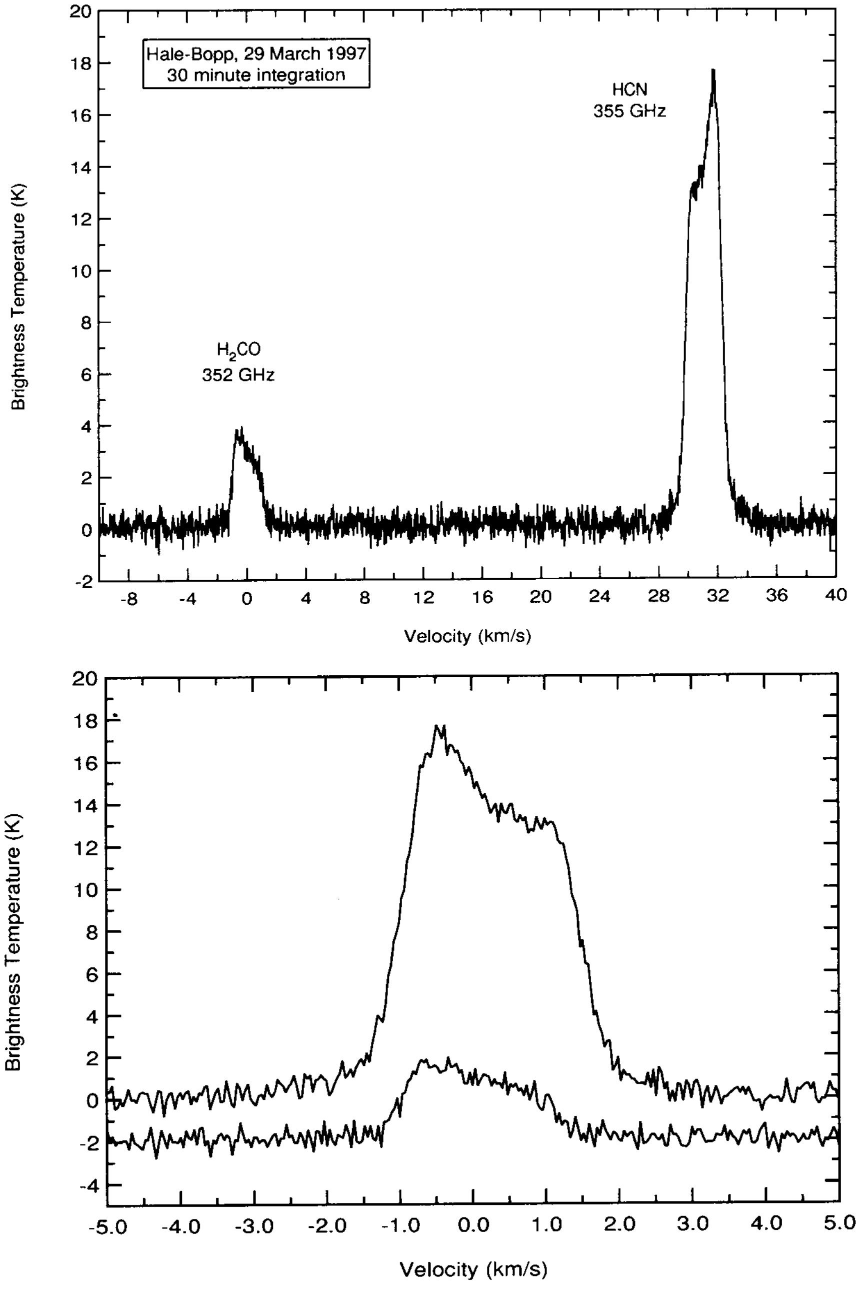

Figure 1. Simultaneous observations of the H_2CO line at 351.769 GHz and the HCN(4-3) line at 354.505 GHz. In Figure 1a (top), the bottom axis is frequency, expressed as the Doppler velocity of the H_2CO line. Because the lines are observed in different sidebands, their shapes are mirror images and HCN appears at an artificially high velocity. H_2CO is in the correct orientation. Figure 1b (bottom) shows the two lines with their correct Doppler velocities. The lower curve in Figure 1b is H_2CO, and it has been offset by −2 K in brightness for clarity.

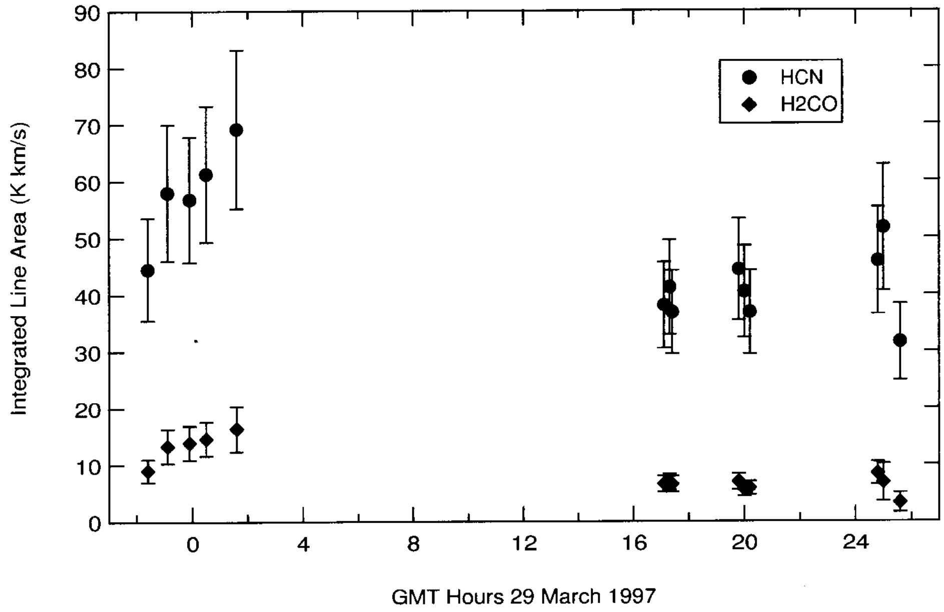

Figure 2. Integrated line areas as a function of time, expressed as GMT hours from the start of 29 March 1997. Error bars are dominated by a 20% uncertainty in the absolute calibration and beam efficiency.

The area under a spectral line is a measure of the species column abundance. In the optically thin case, the relation is linear. We therefore show, in Figure 2, the line area as a function of time for all the data used in our analysis. Each point is based on a spectrum similar to Figure 1. The first was taken on March 28, at 2223 GMT, and the last on March 30 at 0138 GMT. The integration time for each is approximately 5 min, except for the second through fifth: these were only 2 min, and have noticeably higher noise levels. The last three spectra are noisy due to an increase in atmospheric opacity at these times. In Figure 2, we have not shown absolute abundances or production rates in order to avoid the uncertainties associated with that conversion. Error bars are dominated by the 20% uncertainty we allow in the calibration and antenna efficiency. Errors due to spectral baseline and thermal noise are typically less than half the indicated size. There are two suggestive trends in the data. One is that gas abundances appear higher in the first 4 h of data than they do later on. The second trend is for increasing gas production within the first observing period, and perhaps increasing HCN production in the last 8 h. We shall see in the next section, however, there are two possible systematic error sources (antenna pointing and receiver sideband ratio) that must be understood before interpreting these data.

3. Variations in the Observed HCN/H_2CO Ratio

Since we simultaneously observe HCN and H_2CO, the measured ratio of these species is independent of most calibration and pointing errors. Figure 3 therefore shows the ratio of the integrated line areas, HCN/H_2CO, as a function of time. We see that one of the trends pointed out previously is clearly still present: the ratio is different between the first and last 8 hours of observations, jumping from $\sim$4.5 to $\sim$6.0 or greater. While there also remains a suggestion of variation on shorter time scales (such as around 0 h), the error bars do not allow a conclusion in this regard.

The error bars in Figure 3 are determined from the observed rms noise level in each spectrum. (Note that the last two observations have a very large uncertainty due to a relatively high noise level combined with a small H_2CO line area.) The only error source we are aware of which is not accounted for is a possible variation in the sideband ratio. (The sideband ratio is the relative gain of the signal in each sideband. Normal calibration procedures assure that the sum of the two gains is constant, but not the ratio.) Because the receiver was tuned to other species during the gaps in Figure 3, each time we tuned back to the H_2CO/HCN line pair (at -2, 16, 19, and 24 hours) the sideband ratio could be different. This effect could be large enough to explain the long term variations in Figure 3, but only if two uncorrelated sources of error acted in unison each time we tuned our receiver. This is explained below. The conclusion we reach, however, is that the variability apparent in Figure 3 (primarily an increase in the line area ratio of 30% between 2000 and 1700 h) is suggestive of variability on the comet, but is not proof. In the next section we discuss what this variability might mean, if it is real.

The reason that sideband variability alone cannot explain our data is that, if the sideband ratio changed, one line area would appear to increase, while the other decreased. (This is due to our calibration procedure maintaining a constant sum of the gains.) In Figure 2, however, it is clear that both the HCN and H_2CO lines rose and fell in tandem. By itself, this would constitute proof of stability. Unfortunately, we also may have been subject to an antenna pointing error of up to half our beam size. (This error is due to inaccuracies in the model used to relate commanded antenna angles to locations in the sky: it is not an ephemeris error.) It could reduce the strength of both lines sufficiently to mask the “one-up, one-down” signal of the sideband problem. We consider this combination of errors to be unlikely since we did update the pointing by observing a known source each time we tuned, and the pointing would have to have been getting steadily worse to match the trend in Figure 3. A further reason to doubt that antenna pointing errors are consistently offsetting sideband variability is that the antenna pointing model, if wrong, should have similar errors each time we try to point to a given azimuth and elevation. Thus, the error at 0200 h should be similar to the error at 2600 h (one Earth rotation later), but in Figures 2 and 3, we see our data appear quite different. In spite of these arguments, however, we must allow the possibility of a nefarious combination of errors. Note that the sideband ratio would not change between receiver tunings, so

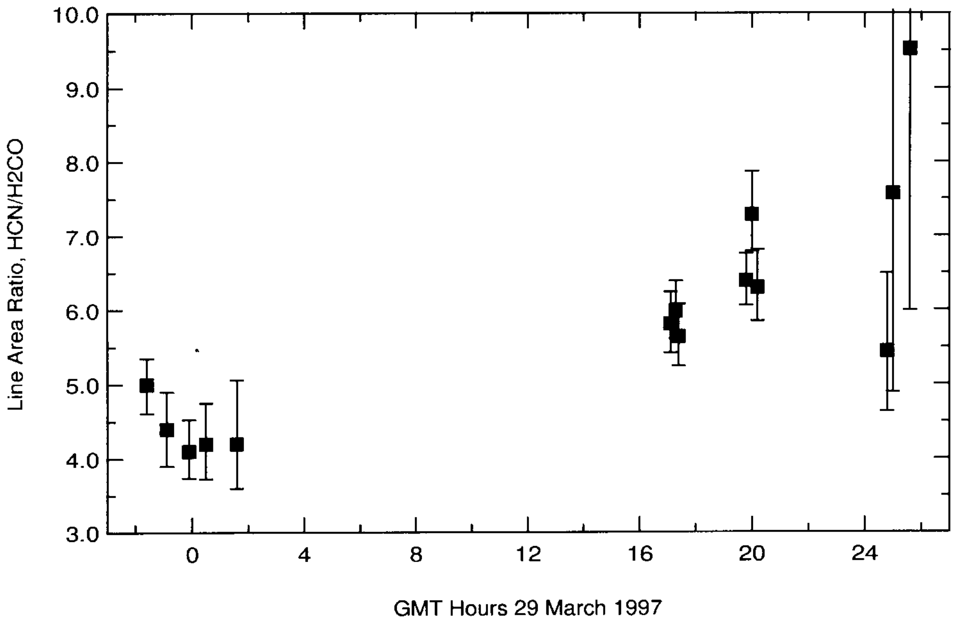

Figure 3. The ratio of the HCN line area to the H_2CO line area, as a function of time. There is a clear trend for an increasing ratio over the 27 h of observation. Variations over times as short as 2 h are present, but these are at the noise level. As discussed in the text, a combination of receiver and antenna errors could be responsible, but we conclude that these data are suggestive of variability on Hale–Bopp.

this potential problem does not affect the relative levels of points within any cluster of observations.

4. Discussion

Based on Figure 3, we believe that the HCN/H_2CO line-area ratio may have changed by ~30% over the course of our observations. Near 0 h, the ratio averages ~4.4, while near 20 h it is between 6 and 7. One interpretation would then be that the bulk composition of the coma was changing over time. This could be caused by an active region on the nucleus, with a different composition than the average, turning "on" or "off". Assuming a nucleus rotation period of ~11.3 h, and a gas expansion velocity of ~0.8 km/s, an active jet rotating into sunlight for 5.6 hours could alter the composition in a 16,000 km wide region of space, which is a significant fraction of our 20,000 km wide antenna beam. Since one would expect significant changes in the jet structure to show up as changes in the line shapes, but no changes are observed (see the discussion of Figure 1b), there is some doubt cast upon this "jet" interpretation. Without further modeling of coma structures, line shapes, and our sensitivity to them, however, we cannot discount this possibility.

An alternative interpretation to time variability is spatial variations within the coma, combined with a systematic error in our antenna pointing during one of the days. Based on observations of known sources, the maximum pointing error to expect is $10''$. This possibility can be considered in some detail because we did attempt to map the comet by moving our beam in $20''$ steps from the comet nucleus. At -0135 h GMT, we find the ratio in the direction of the comet's tail to be 4.4 ± 0.4, which is identical to the "on target" values in Figure 3. Our measurements in directions other than the tail have large error bars due to low signal levels, but favor a high ratio. Therefore, we believe our data could also be explained by a $10''$ pointing error towards the sunward side of the comet, if the HCN/H_2CO line-area ratio is at least 30% larger in this region. There are several mechanisms that might support such an asymmetry in the coma. One might be a difference in the gas or dust emission on the sunward side of the nucleus: this does not require inhomogeneities in the nucleus, but could be a response to direct solar illumination. A second way to support spatial variability would be by the different solar interactions with the sunward and anti-sunward sides of the coma itself. (Keep in mind that H_2CO seems to be generated from a distributed source, presumably sublimating ice or dust grains, while HCN may come predominantly from the nucleus.) Several observing programs mapped spatial distributions (Wink et al., 1997; and other reports in these Proceedings) and may be able to test the spatial variability interpretation.

If we assume that, rather than being an artifact, the HCN/H_2CO line-area ratio actually varied on comet Hale–Bopp by at least 30% (either spatially or temporally), it now needs to be determined how this change relates to quantities of more physical interest; abundance and temperature. If the variations are due entirely to abundance effects, we can conclude that the abundance ratio of the species varies by at least 25%. The argument for this is as follows. In regions of the coma where both species are optically thin, the line area is directly proportional to the column abundance. In regions where both species are opaque (if such regions exist), changing the abundance has minimal effect on line areas. If the coma contained only these two conditions, the 30% change in line-area ratio would require at least a 30% change in the abundance ratio. The situation is different, however, in the intermediate case, where one species is more opaque than the other. In such regions, increasing the abundance of both species equally can result in a change in the line ratio: molecules of the more opaque species added in an opaque region are screened from view, and the line area of the more opaque species changes less. We assessed the magnitude of this effect using a radiative transfer model and assuming all coma gases are generated at the nucleus (this is a worst-case situation because it creates the most optically thick areas). For the observed line areas and ratios, "screening" (primarily of HCN) had only a 5% effect – the abundance ratio of the species was still required to change (either temporally or spatially) by 25%.

Because microwave emission from the coma depends on temperature as well as the gas abundance, we could also interpret the 30% change in line area ratios in terms of temperature variations. Assuming an isothermal coma in thermodynamic equilibrium, we find changes of at least 40 K are needed. This seems too large to be realistic, and the resulting changes in thermal line broadening would likely provide a detectable change in line shape, which we do not observe (see the discussion of Figure 1b). Instead of the entire coma changing temperature, it could also be postulated that either the temperature of HCN changed with respect to the temperature of H_2CO, or each species' weighting function is sampling a different region of the coma and the temperature in one region changed with respect to the other. Neither of these possibilities can be discounted. Note that while rotational temperatures of various species have been measured and none found to deviate appreciably (Biver et al., 1997a, b; Bird et al., 1997), the uncertainty is comparable to the 30% effect we see. A more detailed analysis of the line shape of each species (Figure 1b) may help resolve the temperature/abundance ambiguity. For now, if the observed variations are real, we favor the abundance interpretation because we are unaware of a mechanism for altering the temperature structure of the coma on these time scales without significantly altering gas abundances as well.

5. Conclusion

We measured a 30% variation in the HCN/H_2CO line-area ratio on comet Hale–Bopp over a 27 h time span around 29 March 1997. There is a possibility that this effect is entirely due to a correlation between antenna pointing and receiver sideband ratio errors. If, however, the effect is real, it is due to either temporal or spatial variations within the coma. At this time, we cannot determine whether temperature or abundance ratios are the primary parameter that is changing, but we favor the abundance interpretation. If correct, this means that either the HCN/H_2CO ratio within the coma changed by at least 25% over 16 h, or the ratio on the sunward side of the coma was higher than the rest of the coma by a similar amount.

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