An Analysis of the Variation of Hydrogen Cyanide as Comet Hale-Bopp Approaches the Sun

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Introduction: What are comets?
Where do they come from?
Formation of Comets

• Comets formed while solar system was forming
• Contain frozen chunks of rock and gas from beginning of the solar system
• Long Period Comets and Short Period Comets (A’Hearn et. al. 2001)
  LPCs originated from the Oort Cloud
  SPCs originated from the Kuiper Belt
Comet Hale-Bopp

• Brightest comet ever recorded (Crovisier et. al., 2004)
• LPC – orbital period ~2500 years
• First comet to have argon detected (Stein et. al., 2000)
• Likely originated from the Oort Cloud (Hearn et. al., 2000)
• Rich in organic molecules (Charnley and Rodgers, 2008)
• Discovered in 95’, passed Earth in 97’
Hydrogen Cyanide

- Volatile in comets – found in frozen ice; could be from a process of sublimation or not (Mumna and Charley, 2001)
- Detected in interstellar medium and atmosphere of carbon stars
- $\text{CH}_2+N \rightarrow \text{HCN}+H$
- Atoms and molecules have discrete energy states as described by quantum mechanics. In the case of atoms, the energy states are determined by the interactions between the electron and nucleus.
- When an electron drops down in energy between two of these states, a photon is emitted with an energy corresponding to the difference in energy between the two states. (Milan et. al. 2006)
### Cometary Molecular Percent Composition

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Halley</th>
<th>Hyakutake</th>
<th>Hale-Bopp</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>3.5–11</td>
<td>14–30</td>
<td>12–23</td>
</tr>
<tr>
<td>CO₂</td>
<td>3–4</td>
<td>…</td>
<td>6</td>
</tr>
<tr>
<td>CH₄</td>
<td>&lt;0.8</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>0.3</td>
<td>0.2–0.5</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>1.8</td>
<td>2</td>
<td>2.4</td>
</tr>
<tr>
<td>H₂CO</td>
<td>4</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>HCOOH</td>
<td>…</td>
<td>…</td>
<td>0.09</td>
</tr>
<tr>
<td>HCOOCH₃</td>
<td>…</td>
<td>…</td>
<td>0.08</td>
</tr>
<tr>
<td>CH₃CHO</td>
<td>…</td>
<td>…</td>
<td>0.02</td>
</tr>
<tr>
<td>(CH₂OH)₂</td>
<td>…</td>
<td>…</td>
<td>0.25</td>
</tr>
<tr>
<td>CH₃OCH₃</td>
<td>…</td>
<td>…</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>NH₂CHO</td>
<td>…</td>
<td>…</td>
<td>0.015</td>
</tr>
<tr>
<td>NH₃</td>
<td>1.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>HCN</td>
<td>0.1</td>
<td>0.1–0.2</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Research Gap

• Data has never been analyzed
• Since different comets come from different locations in the galaxy, each one has a different chemical composition
• Once in a lifetime opportunity
• Snapshot of our galaxy
How do the relative amounts of HCN vary as Hale-Bopp is at different distances from the Sun?

$H_0$: The relative amounts of HCN will stay the same while Hale-Bopp is at different distances from the Sun.

$H_1$: As Comet Hale-Bopp approaches the Sun, the relative amounts of HCN will increase.
Securing the Data

- Data provided by astronomer at NASA Goddard Space Flight Center
- Data was collected by using radio receivers on the National Radio Astronomy Observatory 12-meter Telescope in October 96’ and March 97’
- Used to measure raw spectra of HCN
- The data are spectra of molecules which give off radiation at wavelengths between 1mm and 4mm, corresponding to frequencies of 75-300 GHz
- 3 Frequencies: 88.6318 GHz, 177.261 GHz, and 265.886 GHz
Divide data by atmospheric transmission and plot calibrated spectra

Find velocity-integrated line intensity $T'' \Delta V$

Put $T'' \Delta V$ into formula to calculate the column density of molecules of HCN
1.) Plot Calibrated Spectra

- Plotted using GILDAScite
  - Commands inputted telling program which date and frequency number to use
  - Then all observations that match this profile are averaged together and compiled into a format which can be plotted as emission spectra

March 1997, frequency 88.631 GHz, scan 1813-1815
2.) Calculate Line Intensity

- Using GAUSS method to find area underneath the calculated lines

```plaintext
cite file in mar97.class/may97.class/oct96.class {Reads designated file into memory}
cite find {Finds observations}
cite set source HJAB/HAILJABBA/HALEBOPP {Sets the source of the observations}
cite find {Finds observations}
cite set frequency (insert frequency number) {Sets the frequency of the observations}
cite find {Finds observations}
cite set scan (insert scan number) {Sets number of observations}
cite find {Find observations}
cite average /nocheck /resample {Compiles data into a format in which it can be plotted}
cite plot {Plots emission spectra}
cite set window (use cursor to draw window) {Sets window of plot}
cite lines 1/2 (lines depends on how many peaks are present in the graph; boundaries of each lines are placed on boundaries of peak) {Lines are put at peak boundaries}
cite method gauss {Sets that data will be calculated using GAUSS method}
cite base 0 {Cuts off graph at x=0}
cite minimize {Compiles data-final step towards finding area underneath peaks}
cite visualize {Draws green line which shows line what area is being used in calculation}
```
where \( k \) = Boltzmann’s constant, \( T \Delta V \) equals the area of the HCN lines, \( \tilde{\Sigma}_{\text{rot}} \) equals the rotational partition function, \( v \) equals the frequency of the transition, \( S_{ij} \) is the transition line strength, \( \mu \) is the dipole moment of the HCN molecule, and \( T_{\text{rot}} \) is the rotational temperature of the emission, assumed here to be 50 K.
3.) 88.6318 GHz

Data taken on March 7th 1997, on the scan 1813-1815, with two peaks appearing at 0, and 5. There is a slight peak at -8 as well. The area underneath the first peak is equal to .15516, while the second peak is equal to .29287.

Data taken on October 25th 1996, on the scan 672-675, with two peaks appearing at 5 and 0.
3.) 177.261 GHz

<table>
<thead>
<tr>
<th>Line</th>
<th>Area</th>
<th>Position</th>
<th>Width</th>
<th>Tpeak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3637</td>
<td>0.012</td>
<td>1.788</td>
<td>1.7675</td>
</tr>
</tbody>
</table>

Data taken on March 7th 1997, on the scan 1819-1831. Here there is one peak at 0, and the area underneath the peak is equal to 3.3637.

<table>
<thead>
<tr>
<th>Line</th>
<th>Area</th>
<th>Position</th>
<th>Width</th>
<th>Tpeak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.1921</td>
<td>-0.098</td>
<td>1.946</td>
<td>2.5065</td>
</tr>
</tbody>
</table>

Data taken on March 20th 1997. The peak appears at 0. The Second peak, which appears at -20, is believed to be another systems error.
3.) 265.886 GHz

Data taken on March 24th 1997, on the scan 2619-2620, with the peak appearing at 0. The area under the peak is equal to 15.703.

Data taken on March 24th 1997, on the scan 2638-2639. The peak appears at -1, and the area underneath is equal to 15.923.
### 3.) Molecular Rates

<table>
<thead>
<tr>
<th>Mar-97</th>
<th>Date</th>
<th>Frequency</th>
<th>Scan Lines</th>
<th>TRV (area)</th>
<th>Delta (6th)</th>
<th>R (Debye)</th>
<th>Dipole moment (kcal cm² g⁻² l⁻¹)</th>
<th>Rotational Partition Function</th>
<th>Sij</th>
<th>e-Eu/KT</th>
<th>N_tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>done</td>
<td>3/7/97</td>
<td>88631.847</td>
<td>1813-1015</td>
<td>2 #1 = 15516, #2 = 29287</td>
<td>1.422</td>
<td>1.026</td>
<td>2.98 Debye</td>
<td>3.343</td>
<td>0.5555</td>
<td>0.083</td>
<td>9x10⁻¹⁰</td>
</tr>
<tr>
<td>done</td>
<td>3/8/97</td>
<td>88631.847</td>
<td>1949-1955</td>
<td>2 593.838337</td>
<td>1.422</td>
<td>1.026</td>
<td>2.98 Debye</td>
<td>3.343</td>
<td>0.5555</td>
<td>0.085</td>
<td>8562078204</td>
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<tr>
<td>done</td>
<td>3/24/97</td>
<td>88631.847</td>
<td>2603-2606</td>
<td>2 #1 = 21134, #2 = 38704</td>
<td>1.316</td>
<td>0.926</td>
<td>2.98 Debye</td>
<td>3.343</td>
<td>0.5555</td>
<td>0.086</td>
<td>8324907523 x 10⁻¹²</td>
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<tr>
<td>done</td>
<td>3/7/97</td>
<td>1.77781111</td>
<td>1819-1831</td>
<td>1 336370</td>
<td>bad fit</td>
<td>1.422</td>
<td>1.026 2.98 Debye</td>
<td>3.343</td>
<td>0.7500</td>
<td>0.255</td>
<td>6.076474819 x 10⁻¹²</td>
</tr>
<tr>
<td>done</td>
<td>3/20/97</td>
<td>1779261.1</td>
<td>2269-2274</td>
<td>1 404460</td>
<td>1.318</td>
<td>0.94</td>
<td>2.98 Debye</td>
<td>3.343</td>
<td>0.2500</td>
<td>0.255</td>
<td>7.3065107 x 10⁻¹²</td>
</tr>
<tr>
<td>done</td>
<td>3/7/97</td>
<td>1779261.1</td>
<td>2610-2614</td>
<td>1 519210</td>
<td>2.98 Debye</td>
<td>3.343</td>
<td>0.2500</td>
<td>9.367542649 x 10⁻¹²</td>
<td>0.510</td>
<td>0.510</td>
<td>3.161287102 x 10⁻¹²</td>
</tr>
<tr>
<td>done</td>
<td>3/14/97</td>
<td>265866.18</td>
<td>2638-2639</td>
<td>1 934540</td>
<td>bad fit</td>
<td>1.422</td>
<td>1.026 2.98 Debye</td>
<td>3.343</td>
<td>0.2000</td>
<td>0.510</td>
<td>3.361287102 x 10⁻¹²</td>
</tr>
<tr>
<td>done</td>
<td>3/24/97</td>
<td>265866.18</td>
<td>2619-2620</td>
<td>1 1570300</td>
<td>bad fit</td>
<td>1.316</td>
<td>0.926 2.98 Debye</td>
<td>3.343</td>
<td>0.2000</td>
<td>0.510</td>
<td>3.092336337 x 10⁻¹²</td>
</tr>
</tbody>
</table>

| Oct-96 | 10/19/96 | 88631.847 | 194-198    | 1 2240.34              | 3.040 (17)  | 2.98 Debye | 1.38E-23                       | 3.343                         | 0.5555 | 0.083 | 3.141106005 x 10⁻¹⁰ |
| done   | 10/20/96 | 88631.847 | 161-172    | 2 23093.58X        | 3.049 (22)  | 2.98 Debye | 1.38E-23                       | 3.343                         | 0.5555 | 0.083 | 3.237637311 x 10⁻¹⁰ |
| done   | 10/23/96 | 88631.847 | 428-433    | 2 8718.85         | 2.98 Debye  | 3.343     | 0.5555                         | 1.9582861                     | 0.083 | 0.083 | 3.1378122 x 10⁻¹² |
| done   | 10/24/96 | 88631.847 | 558-562    | 2 6982.57          | 2.98 Debye  | 3.343     | 0.5555                         | 1.3378122 x 10⁻¹²            | 0.083 | 0.083 | 1.007225837 x 10⁻¹⁰ |
| done   | 10/25/96 | 88631.847 | 618-625    | 2 #1 = 2.68215E-02, #2 = 4.66173E-02 | 3.053 (27)  | 2.98 Debye | 1.38E-23                       | 3.343                         | 0.5555 | 0.083 | 1.301251174 x 10⁻¹⁰ |
| done   | 10/25/96 | 88631.847 | 672-675    | 2 #1 = 3.71231E-02, #2 = 5.78346E-02 | 2.98 Debye  | 3.343     | 0.5555                         | 1.301251174 x 10⁻¹⁰           | 0.083 | 0.083 | 1.302511741 x 10⁻¹⁰ |
Discussion

- The results show that as Comet Hale-Bopp approaches the Sun, the measured amounts of HCN increase. The data was taken from two time periods, October of 1996, and March of 1997. Comet Hale-Bopp reached perihelion in March of 1997, where it was .914 AU from the Sun. During October of 1996, the Comet was approximately 3.05 AU from the Sun, and the measured amounts of HCN are much lower than they are in March of 1997.

- During October of 1996, the relative amounts of HCN released vary from $8.26 \times 10^9$ to $1.32 \times 10^{11}$, while during March of 1997, when Hale Bopp reached perihelion, meaning it was the closest distance to the Sun that it would be throughout its orbit, the results increased to $3.32 \times 10^{13}$, further confirming the hypothesis.
• The greatest molecular abundances occurred when the comet was closest to the Sun, on March 24th of 1997. On this date, the comet was the closest to the Sun that it would ever be, or in other words, when it reached perihelion.

• The high amounts of molecular abundancies ($10^{13}$ compared to $10^{11}$ and other dates) supports the hypothesis that as the comet comes closer to the Sun, more cometary ice containing HCN is released into the gaseous phase.
Conclusions

• Data supports hypothesis
• Supports the findings of A’Hearn et. al. (2004) and Milan et. al. (2006).
• Limitations
Acknowledgements

- Dr. Michael Kaufman
- My parents
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• Adami, C., Ofria C., & Collier, T. C. 2000, PNAS, 97, 4463


