Far-Ultraviolet Spectroscopy of Comets with the Cosmic Origins Spectrograph on HST

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Overview

• Three comets, 103P/Hartley 2, C/2009 P1 (Garradd), and C/2012 S1 (ISON) (observed after abstract submission) were observed by HST using the Cosmic Origins Spectrograph (COS) since May 2009.
• Each new generation of UV spectrograph on HST allows higher sensitivity and better spectral resolution of the CO Fourth Positive system in the spectral range of 1400 to 1700 Å.
• In most cases, the water production rate was derived from nearly simultaneous observations of the OH (0,0) band at 3085 Å by the Space Telescope Imaging Spectrograph (STIS), allowing determination of the Q(CO)/Q(H₂O) ratio in these comets.
• In all three comets, strong partially resolved emission features due to multiplets of S I, centered at 1429 Å and 1479 Å, and multiplets of C I at 1561 Å and 1657 Å, were observed. The S I intercombination multiplet at 1479 Å is resolved from the allowed resonance multiplet but its excitation source remains unclear.
## COS Comet Observation Parameters

<table>
<thead>
<tr>
<th>Comet</th>
<th>Date</th>
<th>r_helio (AU)</th>
<th>r_dot (km s(^{-1}))</th>
<th>Δ (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103P/Hartley 2</td>
<td>2010 Sep 25</td>
<td>1.15</td>
<td>−9.3</td>
<td>0.22</td>
</tr>
<tr>
<td>103P/Hartley 2</td>
<td>2010 Nov 04</td>
<td>1.06</td>
<td>+2.1</td>
<td>0.15</td>
</tr>
<tr>
<td>103P/Hartley 2</td>
<td>2010 Nov 28</td>
<td>1.14</td>
<td>+9.0</td>
<td>0.27</td>
</tr>
<tr>
<td>C/2009 P1 (Garradd)</td>
<td>2012 Jan 19</td>
<td>1.59</td>
<td>+5.5</td>
<td>1.72</td>
</tr>
<tr>
<td>C/2012 S1 (ISON)</td>
<td>2013 Oct 21</td>
<td>1.23</td>
<td>−37.7</td>
<td>1.53</td>
</tr>
<tr>
<td>C/2012 S1 (ISON)</td>
<td>2013 Nov 01</td>
<td>0.99</td>
<td>−42.0</td>
<td>1.22</td>
</tr>
</tbody>
</table>

**STIS Observations**

<table>
<thead>
<tr>
<th>Comet</th>
<th>Date</th>
<th>r_helio (AU)</th>
<th>r_dot (km s(^{-1}))</th>
<th>Δ (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>153P/Ikeya-Zhang</td>
<td>2002 Apr 20/21</td>
<td>0.90</td>
<td>+29.1</td>
<td>0.43</td>
</tr>
<tr>
<td>C/2001 Q4 (NEAT)</td>
<td>2004 Apr 25/26</td>
<td>1.02</td>
<td>−10.2</td>
<td>0.47</td>
</tr>
</tbody>
</table>
103P/Hartley 2: View from EPOXI and HST
103P/Hartley 2 – HST/COS

lbk606010_x1dsum.fits+lbk609010_x1dsum.fits  FUVA  2410 s

lbk606010_x1dsum.fits+lbk609010_x1dsum.fits  FUVB  2410 s

Lupu CO model, T=75 K, N=1.0e13, FWHM=1.0 Å
COS FUV spectrum – C/2009 P1 (Garradd)

lbws14010_x1dsum.fits  FUVA  999 s

Wavelength (Å)
Brightness (rayleighs Å⁻¹)

C I
He I x3
He I x3

lbws14010_x1dsum.fits  FUVB  999 s

Wavelength (Å)
Brightness (rayleighs Å⁻¹)

S I
S I
weighted Lupu CO model, T=50 K, b=1.0, FWHM=1.0 Å
Comet C/2012 S1 (ISON)
Q(CO)/Q(H₂O) ~ 1.3%, similar to what was obtained on 28 October (~1.5%).
Modeling of the CO Fourth Positive bands

• Model follows the approach of Lupu et al. (ApJ, 670, 1473, 2007), for treating saturation of individual lines in a ro-vibrational band (following slides).
• Average column density in the COS 2.5” diameter aperture is derived from observed spectrum. CO production rate is then calculated assuming radial outflow from a symmetric point source.
• Adjustable parameters include rotational temperature ($T_{rot}$), outflow velocity, and solar flux. We use $T_{rot} = 50$ K (for Garradd, Paganini et al. ApJ (Letters), 748, L13, 2012), an outflow velocity of 0.7 km s$^{-1}$, and a solar flux appropriate to solar activity at the time of observation.
• The uncertainties in these parameters give a derived value of $Q$(CO) reliable to 20—30%.
• From the OH data, a vectorial model fit yields $Q$(H$_2$O) enabling the determination of CO production rate relative to that of H$_2$O from nearly simultaneous observations.
HST/STIS: Comet Ikeya-Zhang
Comet Ikeya-Zhang: CO Fourth Positive bands

## Derived CO Production Rates

<table>
<thead>
<tr>
<th>Comet</th>
<th>Date</th>
<th>$r_h$ (AU)</th>
<th>$\Delta$ (AU)</th>
<th>Inst</th>
<th>N(CO) *</th>
<th>Q(CO) §</th>
<th>Q(H$_2$O) §</th>
<th>Q(CO)/Q(H$_2$O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103P/Hartley 2</td>
<td>2010 Nov 04</td>
<td>1.06</td>
<td>0.15</td>
<td>COS</td>
<td>1.15a</td>
<td>0.0026</td>
<td>0.85</td>
<td>0.003</td>
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<tr>
<td>C/2009 P1 (Garradd)</td>
<td>2012 Jan 19</td>
<td>1.59</td>
<td>1.72</td>
<td>COS</td>
<td>100</td>
<td>2.0</td>
<td>10.</td>
<td>0.20</td>
</tr>
<tr>
<td>C/2012 S1 (ISON)</td>
<td>2013 Nov 01</td>
<td>0.99</td>
<td>1.22</td>
<td>COS</td>
<td>1.50</td>
<td>0.03</td>
<td>2.4</td>
<td>0.013</td>
</tr>
<tr>
<td>153P/Ikeya-Zhang</td>
<td>2002 Apr 20</td>
<td>0.90</td>
<td>0.43</td>
<td>STIS</td>
<td>613b</td>
<td>1.54 ± 0.09b</td>
<td>21.5</td>
<td>0.072</td>
</tr>
<tr>
<td>C/2001 Q4 (NEAT)</td>
<td>2004 Apr 25</td>
<td>1.02</td>
<td>0.47</td>
<td>STIS</td>
<td>684b</td>
<td>1.76 ± 0.16b</td>
<td>20.</td>
<td>0.088</td>
</tr>
</tbody>
</table>

*(10$^{13}$ cm$^{-2}$) §(10$^{28}$ s$^{-1}$)

Apertures: COS 2.5” diameter
STIS: 0.2” x 1.5”

Comet Garradd CO and H$_2$O

Bodewits et al. (astro-ph 1403.0092); following Feaga et al. (AJ 147:24, 2014)
At the 1 Å resolution of COS both the $^3P - ^3D^o$ multiplets and the intercombination $^3P - ^5D^o$ multiplet are resolved.

Relative line intensities of the allowed multiplets can be modeled with solar resonance fluorescence assuming thermal populations of the ground state J levels.
S I multiplets at 1479 Å

S I emission in C/2009 P1 (Garradd)

rh = 1.59
rdot = 5.40
bvalue = 1.0

S column = 1.50e+13 T = 100.0

Lupu CO model, T=50 K, N=1.0e15, FWHM=1.0 Å
Comets Ikeya-Zhang and NEAT

Fig. 7.—Residuals from the spectrum of 153P/Ikeya-Zhang and C/2001 Q4 after subtracting the best-fit CO model \((N = 3.07 \times 10^{15} \text{ and } 3.49 \times 10^{15} \text{ cm}^{-2}, \text{respectively})\). The comet spectra were extracted from a region of 4" width, centered on the comet nucleus. The red line is the predicted H\(_2\) fluorescence spectrum pumped by solar Ly\(/\alpha\) for a column density of \(1.0 \times 10^{14} \text{ cm}^{-2}\) and a rotational temperature of 200 K. Other atomic contributions are shown in blue.
Model fits: Comets Ikeya-Zhang and NEAT

153P/Ikeya–Zhang

C/2001 Q4 (NEAT)
FIG. 1. a and b. Sensitivity calibrated CS$_2$ photoemission spectrum over the wavelength range from 115–170 nm for an electron-impact energy of 100 eV. In Table I, the transitions producing all but the smallest features are identified and their emission cross sections are presented.

C I model fit: C/2009 P1 (Garradd)

If electron dissociative excitation of either CS$_2$ or H$_2$S were significant we would expect to see several Rayleighs of S I ($^1D - ^1D^o$) emission at 1666.9 Å.
## Derived Column Densities

<table>
<thead>
<tr>
<th>Comet</th>
<th>Date</th>
<th>$r_h$ (AU)</th>
<th>$\Delta$ (AU)</th>
<th>Inst</th>
<th>N(C)*</th>
<th>N(S)*</th>
<th>N(CO)*</th>
<th>Q(CO)$§</th>
</tr>
</thead>
<tbody>
<tr>
<td>103P/Hartley 2</td>
<td>2010 Nov 04</td>
<td>1.06</td>
<td>0.15</td>
<td>COS</td>
<td>0.03</td>
<td>1.0</td>
<td>1.15$^a$</td>
<td>0.0026</td>
</tr>
<tr>
<td>C/2009 P1 (Garradd)</td>
<td>2012 Jan 19</td>
<td>1.59</td>
<td>1.72</td>
<td>COS</td>
<td>0.25</td>
<td>1.5</td>
<td>100</td>
<td>2.0</td>
</tr>
<tr>
<td>C/2012 S1 (ISON)</td>
<td>2013 Nov 01</td>
<td>0.99</td>
<td>1.22</td>
<td>COS</td>
<td>0.05</td>
<td>0.5</td>
<td>1.50</td>
<td>0.03</td>
</tr>
<tr>
<td>153P/Ikeya-Zhang</td>
<td>2002 Apr 20</td>
<td>0.90</td>
<td>0.43</td>
<td>STIS</td>
<td>5.0</td>
<td>50</td>
<td>613$^b$</td>
<td>1.54 ± 0.09$^b$</td>
</tr>
<tr>
<td>C/2001 Q4 (NEAT)</td>
<td>2004 Apr 25</td>
<td>1.02</td>
<td>0.47</td>
<td>STIS</td>
<td>1.0</td>
<td>10</td>
<td>684$^b$</td>
<td>1.76 ± 0.16$^b$</td>
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</tbody>
</table>

*(10$^{13}$ cm$^{-2}$)  
§(10$^{28}$ s$^{-1}$)  

Apertures:  
COS 2.5” diameter  
STIS: 0.2” x 1.5”
Summary

• With COS we have observed three comets and found the CO production rate relative to $\text{H}_2\text{O}$ to span two orders of magnitude. Comet C/2009 P1 (Garradd), observed over a long time span by many different observers, showed an unusual behavior in CO/$\text{H}_2\text{O}$ production rates.

• In 103P/Hartley 2, the CO production rate, relative to water, is the lowest ever measured, and beyond the capability of infrared and sub-mm instruments. Data from the EPOXI fly-by of this comet showed an unusually high abundance of $\text{CO}_2$ as well as an extended coma of icy grains.

• The $S$ I intercombination multiplet, $^5\text{D}^o - ^3\text{P}$, at 1479 Å, is resolved from the allowed resonance multiplet, $^3\text{D}^o - ^3\text{P}$ and appears in the same relative proportion to the allowed transition all three comets. The excitation mechanism remains unclear.

• The Rosetta mission, which recently exited hibernation on January 20 of this year, may provide ground truth for some of these questions. Regrettably, its target, comet 67P/C-G, will not be observable by HST for most of its apparition because of solar constraints.
Thanks!

- Heartfelt thanks to Alison Vick, Tony Roman, Merle Reinhart, Dave Sahnew, Bill Workman, and Tracy Ellis (all at STScI) for their expert assistance in planning and executing these time-critical moving target observations.