COMETS AS MOLECULAR/ATOMIC PHYSICS LABORATORIES

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COMETS AS MOLECULAR/ATOMIC PHYSICS LABORATORIES

How to verify a lot of quantum mechanical calculations without doing any quantum mechanics
COMETS AS MOLECULAR/ATOMIC PHYSICS LABORATORIES

High-quality astrophysics with sophomore-level physics
COMETS AS MOLECULAR/ATOMIC PHYSICS LABORATORIES

What I did for my summer vacation last year
Thanks to people who made this possible

- Mike Combi (U. Michigan)
- Walt Harris (U.C. Davis)
- Paul Feldman (Johns Hopkins)
- Hal Weaver (Johns Hopkins Applied Physics Lab)
- Galaxy Evolution Explorer (GALEX) team
  - Karl Forster (Cal Tech)
  - Tim Conrow (IPAC)
  - Susan Neff (NASA/GSFC)
- JPL HORIZONS: Jon Giorgini
Outline

- Background
  - What is a comet – why do we care?
  - How do we “measure” comets?
  - Why do we need accurate molecular/atomic physics to measure comets?
- Measuring the carbon ionization lifetime
- Next step: CO
- Along the way: O
- Final phase: OH
What is a comet?

- Nucleus (10—100 km)
- Head/Coma (neutral emission lines, 100—10^6 km) – **ballistic motion**
- Dust tail (white, 10^7 km)
- Ion tail (blue, 10^7 km)
Why do we care about comets?

- Comets are some of the most primordial material left over from the formation of the solar system
  - Solar system formation models
Why do we care about comets?

- Comets may have delivered water and the seeds of life to Earth, maybe Mars, Venus, etc.
  - Amino acids have been observed
How do we “measure” comets

IDEAL: Cryogenic Nucleus Sample Return (CNSR)

- Bring back a core sample
- Billions of dollars
- Not any time soon 😞

Prialnik 2004
How do we “measure” comets

Next best thing:

- Take the lab to the comet
- Rosetta: European Space Agency (ESA) Orbiter/Lander
- Comet
  67P/Churyumov-Gerasimenko

Astrium - E. Viktor
How do we “measure” comets

First approximation: the **Stardust mission** flew through the tail of comet Wild 2, collected comet dust, and sent it back to Earth.
How do we “measure” comets

Second approximation: **Deep Impact** impactor
Excavated comet material

Deep Impact pre-impact view

Stardust revisit

NAS/PL-Caltech/University of Maryland/Cornell
How do we “measure” comets

Tried and true: Remote sensing
Look at what is coming off of the comet and figure out what it is made of

- Volatiles:

<table>
<thead>
<tr>
<th>Molecule</th>
<th>1P/Halley</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>100</td>
</tr>
<tr>
<td>CO</td>
<td>3.5–11</td>
</tr>
<tr>
<td>CO₂</td>
<td>3–4</td>
</tr>
<tr>
<td>CH₄</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>0.3</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>0.4</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The Mayall 4-meter telescope at the Kitt Peak National Observatory near Tucson, Arizona.
Remote sensing

A spectrum is worth a thousand pictures

103P/Hartly 2 (EPOXI target; Weaver et al. 1992)
Remote sensing

Spectro-imaging is priceless

Carbon 1561 Å and 1657 Å multiplets

Carbon coma
Galaxy Evolution Explorer

- NASA Small Explorer mission
- Works for comets too!
GALEX spectral response

Morrissey et al. 2005

Weaver et al. 1992
Different emission lines have different scale lengths.
Mcphate et al. 1999

FUV
NUV

GALEX
FUV

Area (cm²)

1500
20

Brightness (R Å⁻¹)

Wavelength (Å)

1300 1400 1500 1600 1700 1800

Wavelength (nm)

110 200 300

10 000.00
1000.00
100.00
10.00
1.00
0.10
0.01

H O S C CO

CO (A'Π-X'Σ⁺)

C C O

NH CS CO₂ C₂

S S S
Production rate, $Q(C)$, derived from total emission
$Q(C)$ related to C in the nucleus
Reality: most instruments don’t “swallow” all the light
Aperture corrections
Aperture corrections

- Require accurate knowledge of spatial distribution
- Now measured for carbon (Morgenthaler et al. 2011)

**Key parameters:**

\[ \tau = \text{lifetime} \]
\[ v = \text{outflow velocity} \]
\[ v\tau = \text{scale length} \]
Haser (1957) model: Consider comet nucleus isotropically emitting particles at rate $Q$, velocity $v$, lifetime $\tau$. Derivation is left as an exercise to the reader 😊

$$n(r) = \frac{Q}{4\pi r^2 v} e^{-\frac{r}{v\tau}}$$

$n = \text{number density}$

$Q = \text{production rate}$

$\tau = \text{lifetime}$

$v = \text{velocity}$

$r = \text{dist. from comet}$

2-component Haser model:

“Parent/mother” = 1

“Daughter” = 2

$k = \text{combination of scale lengths}$

$$n(r) = \frac{Q}{4\pi r^2 v_2} k \left( e^{-\frac{r}{v_1\tau_1}} - e^{-\frac{r}{v_2\tau_2}} \right)$$

Integrate along line of sight to convert number density to column density
Carbon is a daughter species

- \( v_1 \sim 1 \text{ km/s} \) (bulk outflow velocity)
- \( v_2 \sim 4 \text{ km/s} \) (ejection velocity)
- > 3 \( \times 10^5 \) km, just carbon ionization

Best-fit Haser model determines carbon ionization lifetime
Best-fit Haser model determines carbon ionization lifetime

\[ n(r) = \frac{Q_k}{4\pi r^2 v_2} e^{-\frac{r}{v_2\tau_2}} \]

Problem: BACKGROUND!
Carbon lifetime: BACKGROUND!

Comet moves: Stars can be erased
Background exposure ~1 month prior – good enough?
Carbon lifetime: BACKGROUND!

- What changes over a FOV of 1 degree?
- Not the Galaxy
- Solar system? FUV zodiacal light not bright enough
- Earth’s atmosphere: Airglow
  - Photochemical effect
- Correction is analogous to extinction
- Spent summer vacation picturing GALEX orbit and Earth’s shadow in 3D
- Aeronomy

Sujatha et al. (2009) airglow used solar activity
Carbon Lifetime vs. Airglow

- Airglow ~uniform over 1 degree
- Constant offset of background image

Solar photoionization only
Comet Machholz’s heliographic latitude was 30° during solar min

Edge of slow solar wind zone

Table 3
Carbon Ionization Lifetimes (Rates) at 1 AU

<table>
<thead>
<tr>
<th>Process</th>
<th>Quiet Sun Slow Wind&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Quiet Sun Fast Wind&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Active Sun Slow Wind&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C + h\nu \rightarrow C^+ + e^-$</td>
<td>24 (0.41)</td>
<td>24 (0.41)</td>
<td>10 (0.92)</td>
<td>Huebner et al. (1992)</td>
</tr>
<tr>
<td>$C + H^+ \rightarrow C^+ + H$</td>
<td>17 (0.59)</td>
<td>40 (0.25)</td>
<td>17 (0.59)</td>
<td>Rubin et al. (2009)</td>
</tr>
<tr>
<td>$C + e^- \rightarrow C^+ + 2e^-$</td>
<td>48 (0.21)</td>
<td>20 (0.05)</td>
<td>48 (0.21)</td>
<td>Rubin et al. (2009)</td>
</tr>
<tr>
<td>Total predicted</td>
<td>8.2 (1.21)</td>
<td>14 (0.71)</td>
<td>5.8 (1.72)</td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>7.1–9.6 (1.0–1.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes.

<sup>a</sup> $v = 400$ km s<sup>−1</sup>, $n_e = 10$ cm<sup>−3</sup>.

<sup>b</sup> $v = 750$ km s<sup>−1</sup>, $n_e = 2.5$ cm<sup>−3</sup>.

Morgenthaler et al. 2011
Results

- For carbon, solar wind can be more important than solar photoionization!
- **IMPORTANT**: standard reference (Huebner, Keady, and Lyon 1992) only includes photorates
- Solar wind ionization important for all long-lived species
  - Photo lifetimes > 500,000 s
  - e.g. H, C, O, CO
- Previous production rates need to be revisited!
- Comet “carbon puzzle” (Festou 1984) may be solved
Results

- Verified ionization cross section calculations for carbon over a wide range of photon energies
- Verified carbon-proton charge exchange cross section
- Verified carbon-electron collisional cross section
Results: circumstantial evidence?!

- Verified ionization cross section calculations for carbon over a wide range of photon energies
  - Assume solar spectrum is well known
- Verified carbon-proton charge exchange cross section
  - Assume solar wind speed and density well known
- Verified carbon-electron collisional cross section
  - Assumed comet was in slow solar wind
Mcphate et al. 1999

GALEX
FUV: CO

FUV  NUV

Wavelength (nm)

Area (cm²)

Wavelength (Å)

Brightness (R Å⁻¹)

CO (A'π-X'Σ⁺)

S

C

C²

CO₂

NH

CN

OH

C O H S

10 000.00

1 000.00

100.00

10.00

1.00

0.10

0.01

110 200 300

1300 1400 1500 1600 1700 1800
Next step: CO with FUV grism

Morgenthaler et al. 2011
Why does [OI] oxygen distribution in Hale-Bopp look like a comet?

Metastable [OI] prompt emission really traces H₂O and OH

Morgenthaler et al. 2001
Residuals aren’t as clean

Need 3D coma models – jets, emission asymmetries, ion lines?
Conclusions

- It is possible to reliably measure atomic and molecular lifetimes using wide-field observations of comets
  - C was easy – isotropic
  - CO will be harder with grism data
  - OH requires sophisticated coma models
- GALEX could be used as an upper-atmosphere research station (700 km altitude)