Observations of comets with high-resolution, wide-field instruments

Jeff Morgenthaler

Outline

Who is Jeff Morgenthaler?

Comet intro

Evolution of H₂O in cometary comae

Discovery of problem with OH photodissociation cross section

Partial list of things to do

Instruments

Observations of comets with high-resolution, wide-field
Jeff Morgenthaler

1988–1995 soft X-ray instrumentation
– Wisconsin junior graduate student: X-ray Quantum Calorimeter (XQC) sounding rocket payload development (McCammon et al. 2002)
– 1998–2002 Wisconsin Postdoc: Analyze comet Hale-Bopp optical emission line data
  – Pharmacy thesis: Shuttle STS-54 payload – Diffuse X-ray Spectrometer (DXS) (Morgenthaler 1998; Sanders et al. 2001)
  – New twist: X-rays from charge exchange of solar wind ions, a process observed in comets (Lisse et al. 1996; C ravens 1997)
  – Standard model: X-rays from a million degree plasma in the interstellar medium
– 1995–Present soft X-ray background
  – Morgenthaler et al. 2001, 2002a, b; Harries et al. 2002; Oliversen et al. 2002)


2004–? University of Washington postdoc: Get Walt Harris tenure
Where do comets come from?

The primordial solar nebula

• Nebular collapse, planetary formation

• Dynamical evolution of primordial * interstellar

• Leftover planetesimals, * dynamically ejected by planets

• Rocky asteroids (2–3.5 AU)

• Icy Kuiper belt objects (50–500 AU)

• Oort cloud objects (500–5,000 AU)

Dynamical things happen, planet orbits change, etc.
What does a comet look like?

Based on what we see coming off of comets, they are:

- Mostly water
- 5–15% CO
- Other molecules, including organics
- 1% “dust”
- More-or-less homogeneous (as if interstellar dust has any typical form)
- May or may not be similar to interstellar dust
- 10% “dust”

Dirty snowballs

• Comet fragments look like comets
• More-or-less homogeneous
• (as if interstellar dust has any typical form)

What does a comet look like?

- 4 -
What happens to comets when they get close to the sun?

- Comet nucleus often splits
- Comet evolves over many perihelion passages
- Dust is liberated – particles follow comet orbit modified by radiation pressure
- Accretion modified by collisions with neutrals
- Ions accelerated by solar wind
- Solar radiation and charge exchange with solar wind ions ionizes some coma gas
- Ion tail
- Like a planetary atmosphere without gravity
- Density ranges from near atmospheric to interplanetary
- More-or-less spherical distribution of gas
- Form coma
- H₂O, CO, other volatiles sublime

Deep Impact mission may help decide

Pudding with a skin vs. a ball of ice

Need ground-based observations 2005 July 4
Fig. 1. — Comet Hale-Bopp (Image courtesy of H. Mikuz & B. Kambic)
Understanding evolution of $\text{H}_2\text{O}$ in cometary coma

- Ions interact with the solar wind (ion tail) and drag through neutrals (mass loading).
- Neutral $\text{H}_2\text{O}$ and photodissociation products expand isotropically unless a strong resonant line induces an inwards force (Na and H).
- Different parts of solar spectrum do different things to $\text{H}_2\text{O}$.
- Reciprocal of the sum of reaction rates is the total lifetime.
- Need a good solar spectrum and $\text{H}_2\text{O}$ cross section to figure out where everything goes.
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Quiet sun, at 1 AU, water lifetime = 83000 s (23 hours).

- Ratio of each reaction rate to total is the branching ratio (BR).
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$\text{H}_2\text{O}$ photodissociates and ionizes in sunlight.
The velocity of $14$ km s$^{-1}$, appropriate for Hale-Bopp 1997 early March.

<table>
<thead>
<tr>
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<th>BRN</th>
<th>Quiet Sun</th>
<th>Active Sun</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>H</td>
<td>196</td>
<td>437</td>
<td>458</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>742</td>
<td>860</td>
<td>623</td>
<td></td>
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<tr>
<td>H</td>
<td>108</td>
<td>855</td>
<td>105</td>
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**Table 1. Photodissociation Branching Ratios**

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<th>Reaction</th>
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<tr>
<td>$\text{H}_2$</td>
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<tr>
<td>$(\text{A})\text{O} + (\text{H}_2\text{O}) \leftarrow \text{aH} + \text{O}_2$</td>
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Observables

\[
\frac{(B_{13})(B_{22})(B_{33})}{(a_I)_O} = (\text{H}_2O)O
\]

- OH resonant fluorescence is observed in the near UV at 3080 Å – interpretation is complex.
- Much less quenching than radio transitions
- OH rotational transitions are observable in the radio at 18 cm – these transitions are easily quenched (e.g., Schloerb et al. 1988).
- \( Q(\text{O}_p) \) depends only on aperture photometry and branching ratios.
- No complex \( g \)-factor
- The forbidden \( \text{O}_v \) transition occurs in \( \text{H}_2O \) at 18 cm (Froese Fischer & Saha 1983) via the bright forbidden 6300, 6363 Å doublet.
- \( (a_I)_O \) decays promptly to the metastable state.
- OH rotational transitions are observable in the radio at 18 cm – these transitions are easily quenched (e.g., Schloerb 1988).
- \( \text{H}_2O \) is hard to observe directly – "hot band fluorescence" in IR (Mumma et al. 1996).

\textbf{Observables}

- 6-
Problem

From other datasets, \textquote[1998]{Find} results derived from observations of the forbidden oxygen lines are nearly always yielding water production rates larger than those derived \textquote[1998]{Find}.

Observational difficulties:

- If [O I] 6300 \AA\ observations are so easy, why do we get it wrong?

- Cometary redshift variation
- Convensional narrow-band filters don't work — if narrow enough, lose too much to
- Spectral separation from airglow requires \(\Gamma\) 10 km s\(^{-1}\) resolution
- Background subtraction works if airglow stable
- Minimum spectral resolving power is \(\gamma\sqrt{\gamma/\gamma}\) \(\approx\) 4000 or 80 km s\(^{-1}\)
  
  (geocentric velocity dependent)

Must separate cometary [O I] from cometary NH\(_2\) and airglow [O I]
Observational difficulties have been solved

High resolving power

* Bonus: high sensitivity due to large FOV and ability to match FOV to coma size, even at...
Fig. 2. — Wisconsin H-alpha Mapper (WHAM) spectrum (left) and image (right) of comet Hyakutake on 1996 March 23. Analysis conducted by high school interns Michelle Krok and Kyle Ripp.
Fig. 3.—WHAM spectrum (left) and image (right) of Comet Hale-Bopp from 1997 March 5 showing relative ease of [O I] detection even over an airglow-dominated FOV. Resolving power of the WHAM Fabry-Perot is ~30,000 for 10 km s\(^{-1}\) (Tufte 1997; Morgenthaler et al. 2001; Haffner et al. 2003). Note unexplained tailward extension in the [O I] distribution.

Note unexplained tailward extension in the [O I] distribution.
Problem intensifies and suggests a solution

- Observations already exist for all of these
  - Velocity resolved observations needed to constrain energetics – BR4
- OH radio or optical data needed to constrain OH lifetime
  - This work shows BR3 needs to change
- Need to publish a paper on this effect

Wide-field \([\text{O I]} \, 6300\,\text{Å}\) observations of Comets Hyakutake and Halley show a similar

\[ \text{Wide-field [O I]} \, 6300\,\text{Å} \text{ observations of Comets Hyakutake and Halley show a similar} \]

- Only error could be in the branching ratios (Equation 1)
- No model dependent aperture correction needed

(Morfill et al. 2001)

\[ \text{WHAM observations corroborated by [O I] observations of three other instruments} \]

\text{WHAM spectroscopic observations were sensitive enough (0.1 R sensitivity limit in 30 s exposures) to detect all the [O I] emission coming from Hale-Bopp} \]

3–4 times higher than other techniques

\[ \text{Wide-field [O I]} \, 6300\,\text{Å} \text{ observations of Hale-Bopp yielded [OH]} \]

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Fig. 4.—Hal-Bopp $\langle H_2O \rangle$ values from various works (Morgenthaler et al., 2001).
Fig. 5.—Comet Hale-Bopp, \( \nu \text{H}^0 = 0.9 \text{ km s}^{-1}, \nu \text{OH} = 3.3 \text{ km s}^{-1} \).
Wide-field observations of comets motivate modification of OH photochemistry. Large amounts of data exist to constrain the photochemical models of OH photochemistry. Several effects seen in the Halley-Bopp data have not even been touched. Only some of these data have been properly reduced. Tailward asymmetry in [O I] 6300 Å emission and asymmetry in [O I] 6300 Å emission have not even been touched.

Summary

- Use of CCD cameras has increased complexity of data reduction and analysis by more than one million-fold.
- That is just water!
- Observations of H₂O⁺
- Hyakutake dust images
- Hyakutake HCN
- We need millions more graduate students.
- We need to get efficient with those we have.
- Computers (which are a waste of time!) are probably the answer.
- We need millions more graduate students.
- Weneedmillionsmoregraduatestudents.
- Weneedtogetefficientwiththosewehave.
- Computersonareawastetim!
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- Computersonareawastetim!
REFERENCES


-20-


Oliversen, R. J., Scherb, F., Smyth, W. H., Feed, M. E., Woodward, R. C., Marchali,

Collisional Quenching of Cometary Emissions in the 18 cm OH Transitions,

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