Jeff Morgenthaler

About Me

  - MIT CCD labs senior thesis: Soft X-ray Quantum Efficiency of Prototype ASCA CCD detectors (Morgenthaler 1990)
- 1995–Present soft diffuse X-ray background, ISM data analysis
  - Shuttle STS-54 payload: Diffuse X-ray Spectrometer (DXS) (Morgenthaler 1998; Sanders et al. 2001)
- 1997–2002 Comet Hale-Bopp data analysis of optical emission lines ([O I], [C I], [O II], [C II], [O III], [S II]: Harris et al. 2002; Olsen et al. 2002; McCammon et al. 2002)
  - University of Wisconsin, X-ray Quantum Calorimeter (XQC) sounding rocket payload development (Morgenthaler 1990)
- 2002–Present Iopla torus data analysis
  - MIT CCD lab senior thesis: Soft X-ray Quantum Efficiency of Prototype ASCA CCD detectors (Morgenthaler 1990)
Oxygen Emission in Io’s Atmosphere as a Probe of the Plasma Torus

Basics

Outline

Oxygen Emission in Io’s Atmosphere as a Probe of the Plasma Torus
Fig. 1. — Mercury compared to 7 large moons of the Solar System (Kaulfman & Freedman 1999).

- The most volcanic body in the solar system
- About the same size as Earth's moon
- One of the big 7 moons in the solar system

Io: the moldy pizza
Other atmospheric constituents: $S^2, S, O, N_2, K, Cl, Na, Cl, H$

Directly or indirectly the primary source of Io's atmosphere

Material released = SO$_2$, SO$_3$

Caused by tidal forces between Io and Jupiter which are maintained by orbital resonances with Europa and Ganymede ($2 \times$ and $4 \times$ period of Io)

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Volcanism on Io

Fig. 2.—Evidence for volcanism on Io (http://galileo.jpl.nasa.gov/images/io/ioimages.html).
Io Immerged in the Jovian Magnetosphere

- Jupiter's magnetic field is tilted by 10° with respect to rotation axis, offset from center of rotation by 0.13 R
- Rotates every 9.925 hours
- Ions bound longitudinally to field lines but free to move in latitude
- Flow of material down magnetic field induces east-west electric field
- Centrifugal and magnetic forces balance so torus tilts 7°
- Warm outer torus: θ = 5°; with Io's orbit, not tail
- Ribbon near Io's orbit: highest density
- Cold inner torus: inward diffusion
- Various torus structures:
  - Flow of material down magnetic field induces east-west electric field
  - Centrifugal and magnetic forces balance so torus tilts 7°
  - Ions bound longitudinally to field lines but free to move in latitude
  - Rotates every 9.925 hours
  - Not a simple dipole
- Plasma interaction with Io (and other moons) is primary atmospheric loss mechanism
- Io orbits every 42.5 hours; ions whip around and hit the other side of Io at 57 km s⁻¹
- Vertically and radially through these structures

In the frame of reference of the torus, Io moves +0.75 R vertically and +0.75 R² radially through the torus.
Fig. 3.—Visualization of Jovian magnetic field showing Io flux tube, Na cloud, S II ions (http://www.lowell.edu/users/spencer/digipics.html).
Narrow-band Images of the Torus

Fig. 4.—Narrow-band images of S II 6731 Å (top left) and Na 5890 Å (bottom left) in the Jovian system (Courtesy N. M. Schneider & J. T. Trauger). Right: Portable Io Torus Tool (PITT) model of S II 6731 Å. (Courtesy R. C. Woodward).
Fig. 5.—Io’s position in the rest frame of the plasma torus at eastern and western elongation (Oliversen et al. 2001, fig. 7). Contours indicate electron density based on Voyager data (Bagenal 1994).
All kinds of interesting dynamics having to do with a conducting obstacle in a plasma flow

**Io/Plasma Interactions**
Fig. 6—STIS O I $\lambda 1356$ Å image of Io at eastern elongation (Retherford et al. 2000; Retherford 2002). Orange circle is O I $\lambda 1359$ Å emission.
Ground-based observations of [O I] 6300 Å

- Detected in 1990 (Scherb & Smyth 1993)
- McMath-Pierce solar telescope, stellar spectrograph

- 1.5 m telescope, $f = 76.2$ m
- Unocculted beam (no diffraction spikes)
- Works best in the ecliptic

- Beam focused onto a Bowen-Walraven image slicer with a 5'2 × 5'2 FOV

- Echelle spectrograph
- $\tan \theta = 2$
- lines = 20,100 per inch
- $R = 120,000$ at 6300 Å (50 milliÅ, 2.5 km s$^{-1}$)

- TICCD similar to HST WFPC I (i.e. old, slow readout)

- No adult supervision

- Temperamental, hard to repeat alignment procedures (working on that)

- Available at night nearly continuously (share with one other user)
Fig. 7 — McMath-Pierce Solar Telescope. Figures courtesy of NOAO/AURA/NSF.
Fig. 8.—McMath-Pierce solar telescope facility Stellar Spectrograph (SSG).
Fig. 9.—Processed $\mathrm{I\ O\ II}$ 6300 Å spectral image recorded 2002 Jan 26 by the stellar spectrograph at the McMath-Pierce solar telescope facility (upper). Spectral extractions are shown below in the dispersion (middle) and cross dispersion (lower) directions. Seeing this night was $\sim 3''$. 
Fig. 10—Unusual spectrum recorded 1997 Oct 14. CCD is binned in the Y direction—that is not what is unusual about this spectrum.
Within a few weeks of completing first version of automated fitting software

- Automatically extracted all spectra in 6 days of computer time (completed 2003 June 26)
  - Data are corrected or re-reduced using global trends
  - Analysis programs find patterns (e.g. fit polynomials to parameters that vary slowly with time)
  - Results stored in an IDL astro-util ZDBASE
  - Robust algorithms process the data one time through

Developed automated data reduction and spectral fitting software using basic artificial intelligence techniques

- Unacceptable for Planetary Data System (PDS) submissions
- Not interested in spending my NRC fellowship hand reducing 2400 spectra

Oliver sen et al. (2001) report on hand reduction of ~1000 spectra

- Over 13,000 calibration (bias, flat, comp, etc.) images
- Over 3400 spectra recorded since 1990

Later, Rinse, Repeat
Automated Fitting Software

Parameterized Function Object (PFO)

- Object-oriented non-linear least-squares curve fitting routine
- Allows fitting function to be easily modified at runtime
- Written in IDL (Interactive Data Language, v5+)
- Object-oriented non-linear least-squares curve fitting routine
- Based on astro-utilities package MPFIT

Solar System Objects (SSO)  
- Line Catalogs (LC)
- Read, sort and merge line lists from state-of-the-art solar (Moore et al. 1996; Pierce & Breckenridge 1973; Allende Petit & Garcia Lopez 1998) and astrophysical (e.g. HITRAN; Rothman et al. 2003) line catalogs

- Goat Fraunhofer?
- Handles multi-reflection, multiple Doppler shifts
- Builds models to be passed to PFO (interfaces LC to PFO)

- Line Catalogs (LC)
- Based on astro-utilities package MPFIT
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Free parameters are: dispersion relation, solar and Io Doppler shifts, continuum flux, line equivalent width and line widths (Voigt profiles are used for strong lines).
Fig. 11.—SSO fit to „unusual spectrum” recorded 1997 Oct 14. 27 lines were used in the fit (22 Fraunhofer).

Minimum equivalent width $EW = 0.5 \, \text{mA}$, $10 \, EW = 4.2 \pm 0.6 \, \text{mA}$. With $104$ degrees of freedom,

$\chi^2 = 17.4$ with $104$ degrees of freedom.
Fig. 12.—Narrower spectral range view of Fig. 11.
Fig. 13.—Comparison between IO \[I\] intensities fit by hand and an early version of the automatic fitting software.
Fig. 14 — Comparison between $I_0 [1\,0\,1]$ intensities fitted by hand and the current version of the automatic fitting software.
Fig. 15.—Io $I_O$ Doppler velocity vs. Io geocentric ephemeris velocity (Oliverson et al. 2001, fig. 2).

![Graph showing the relationship between measured geocentric velocity and JPL ephemeris geocentric velocity.](graph.png)

- Geocentric velocity $= 0.57$ km/s
- RMS deviation from predicted

Measure geocentric velocity (km/s)

JPL EPHemeris geocentric velocity (km/s)
Link between plasma and \( \text{O}^+ \) emission seems to be an effective in situ proxy for torus plasma density.

Even if torus was a simple doughnut, plasma conditions at Io should correlate with Io's magnetic longitude.

\( \text{O}^+ \) emission seems to track the data well in some cases (Oliversen et al. 2001).

Oliversen et al. (2001) show this correlation based on 1000 measurements recorded over 10 years.

Detailed (but static) model of the plasma torus can track the data well in some cases (Oliversen et al. 2001, figs. 10–11).

Torus rotates faster than Io orbits (57 km/s at Io relative to Io's orbit).
Fig. 16.—Measured Io [OI] intensities over a 10-year period as a function of Jovian magnetic longitude (system III) (Oliverson et al. 2001, fig. 4). Solid line is average over 10° bins.
Fig. 17.—Measured and modeled [O I] 6300 Å emission from Io (Oliversen et al. 2001, figs. 10–11).
Our "unusual day," 1997 Oct 14 happens to be during an HST/STIS observation (Roesler et al. 1999).

Persistent, at least repeating azimuthal asymmetry is seen in the \([\mathrm{S\ II}\ 6731\ \AA}\) torus at this system III longitude during this time period.

STIS sees neutral and ion emissions increase.

Simultaneous \([\mathrm{S\ II}\ 6731\ \AA}\) images of the torus are generally included in the \([\mathrm{O\ I}\] observing campaigns (e.g., Woodward et al. 2000).

Correlating Multiple Datasets
Extended emission from the torus is seen in the ion lines.

Fig. 18.—Sum of raw STIS data 1997 Oct 14 (Roessler et al. 1999, fig. 1).
Fig. 19. S II 1256 Å profiles on 1997 Oct 14 for each of the STIS G140L images. The edges of the disk of Io are shown as dotted lines. PITT model of Io's emission is shown (dashed lines) and scaled and offset to match data (solid lines).
Fig. 20—S II 1256 Å profiles on 1998 Aug 23. Compare to fig. 19.
Fig. 21.—Comparison of Io atmospheric emissions for neutral (top) and ion (bottom) ultraviolet emission lines from HST/STIS and the $[O I]$ 6300 Å emission line (middle). The UV ion results depend on the subtraction of the background torus. Peak in flux occurs before peak calculated by model.
Fig. 22. — Model Io [O I] surface brightness vs. observations for 1997 October 14. Simultaneous HST/STIS ultraviolet measurements for O and S emissions from Io were obtained in the shaded areas.

Model (2 x 10^{15} \text{ cm}^{-2})

Observation

October 14, 1997 (West)
Images from 1999 (last panel) and other authors (e.g., Hufnagel et al. 2000) show asymmetries in the $\text{S}^{\text{II}}$ 6731Å torus (Woodward et al. 1997). Jupiter is attenuated by a neutral density filter. The Galilean moons, such as Io, interfere with the observations. A persistent or at least repeating azimuthal asymmetry in the $\text{S}^{\text{II}}$ 6731Å torus is seen in the 1997 Sept–Oct timeframe (Woodward et al. 2000). Images from 1999 (last panel) and other authors (e.g., fig. 4) do not always show asymmetries.

Fig. 23.—Narrowband images of the Io torus in $\text{S}^{\text{II}}$ 6731Å. Jupiter is attenuated by a neutral density filter.
We can begin to understand the dynamics of the torus system.

Ground-based \([\text{O I}] 6300\) \AA\ observations can be used as a proxy for torus activity.

**What does it mean?**

- To brighten in \(\text{UV} \) ion lines (model dependent)
- To brighten in neutral \(\text{UV} \) and optical lines on 1997 Oct 14
- Enhancement in plasma torus seen in STIS data around 1997 Oct 14
- Azimuthal enhancement in the plasma torus that seems to persist over at least a several week time period

**Do we have a believable “smoking gun?”**

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Future plans

- Full reduction of ground-based O [I] data needed, complete with upper limits on days with weak signal
- Close to closing the loop on fully automated spectral extraction and fitting process
- Unbiased statistical treatment essential for believability of O [I] 6300 Å dataset
- Web interface to ZDBASE of Oliversen et al. (2001) results is operational
- Continuous reduction of S II 6731 Å images, improvement of analysis techniques are needed
- Complete analysis of STIS ion lines
- Correlation with other datasets (e.g., volcanic activity, positions of other moons, flux tube footprint, etc.)
REFERENCES


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