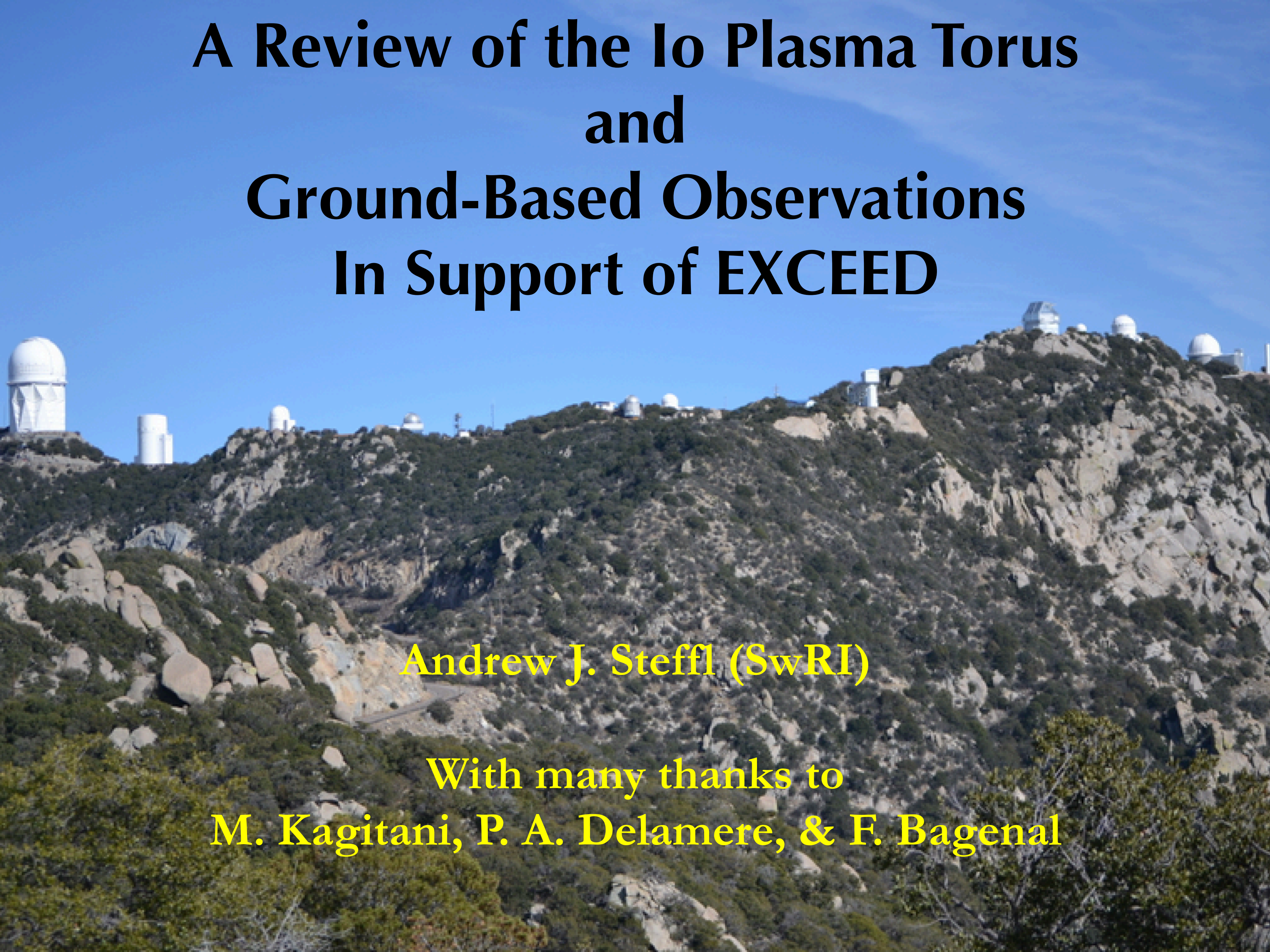
Abstract

- In this presentation, I give a brief review of what the Io plasma torus is, how it is formed, and show some UV spectra of the Io torus obtained by the UVIS instrument on the Cassini spacecraft. I then describe the ground-based observing campaign to obtain optical wavelength spectra of the Io torus from the Kitt Peak National Observatory's 4m telescope in January 2014. Finally, I show how models of the Io torus using a "neutral cloud theory" approach can yield insights into some of the counter-intuitive behavior of the Io torus.



A Review of the Io Plasma Torus and Ground-Based Observations In Support of EXCEED

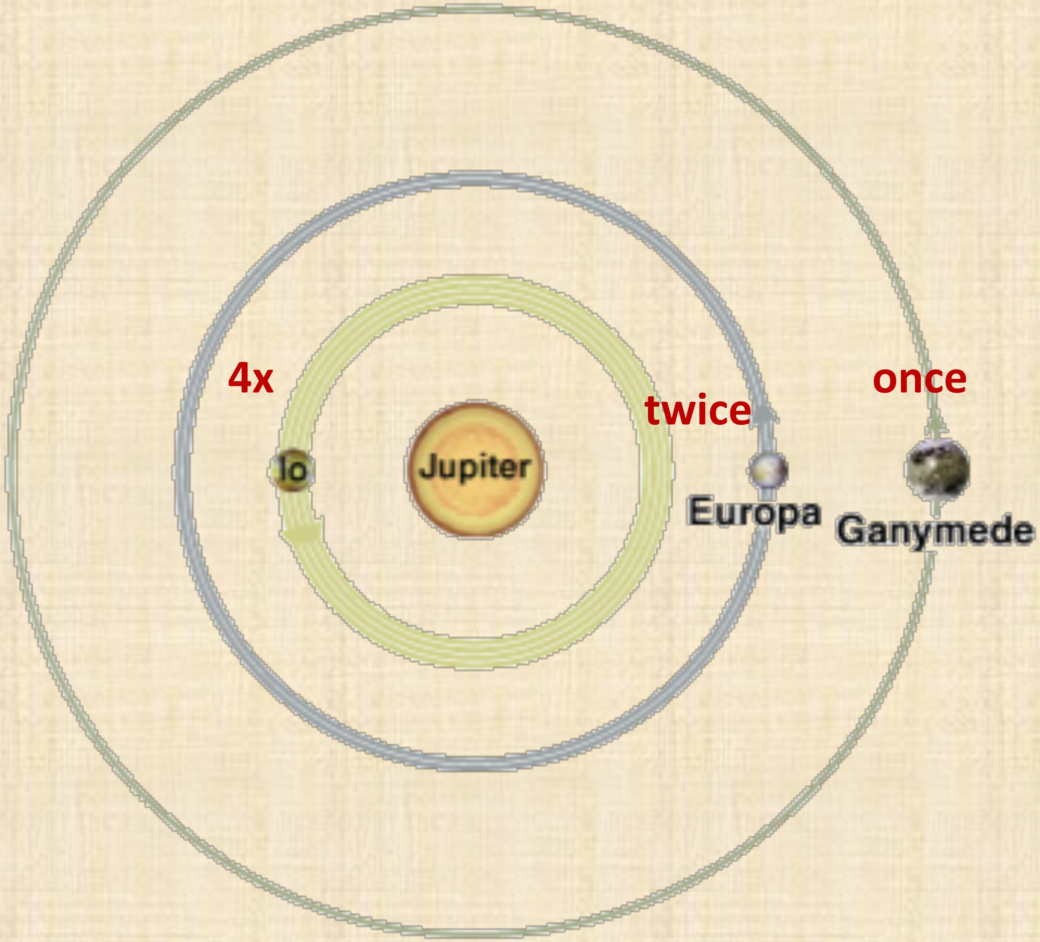
Andrew J. Steffl (SwRI)

With many thanks to
M. Kagitani, P. A. Delamere, & F. Bagenal

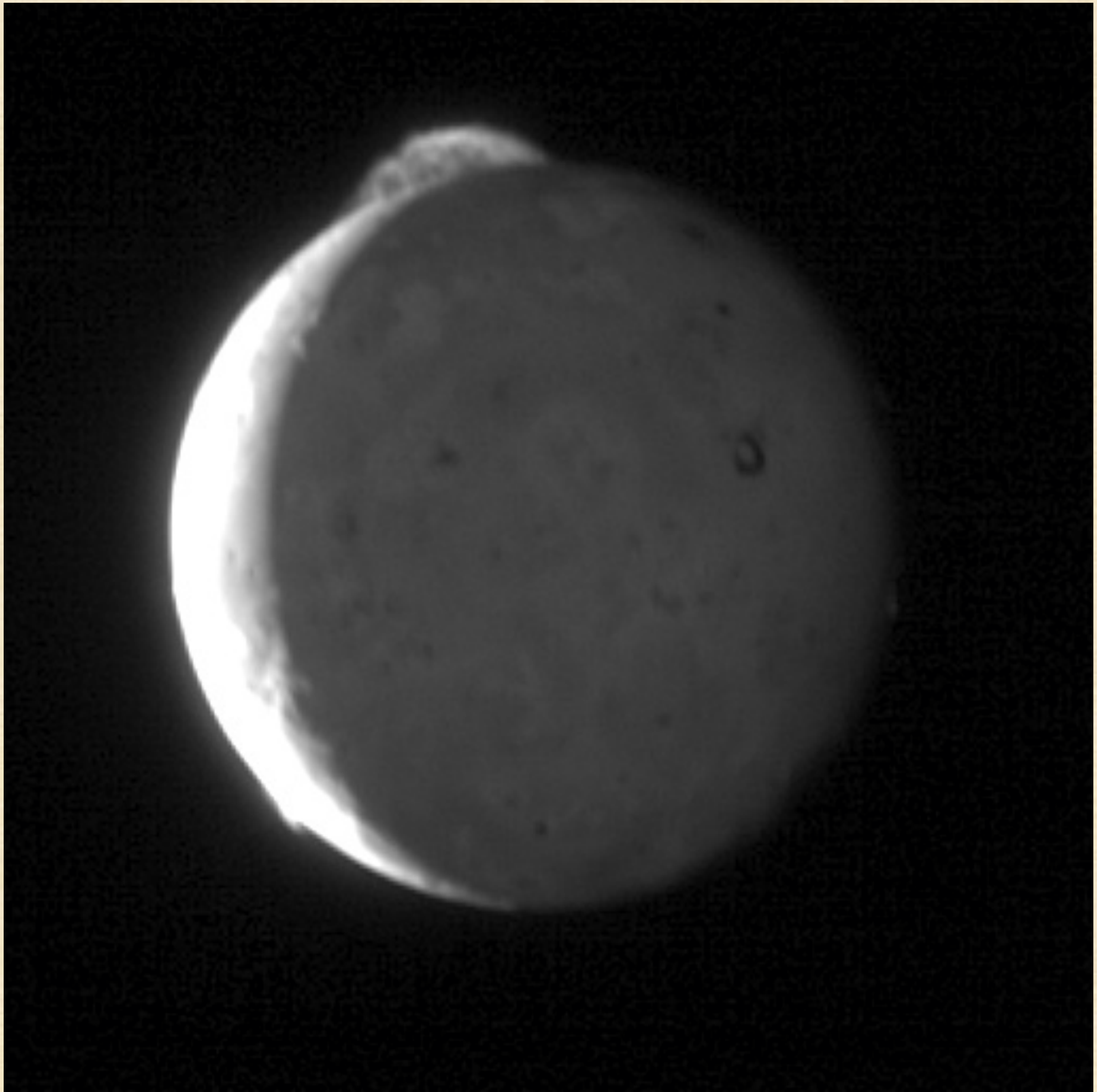
Orbital Resonances
Io - Europa - Ganymede

- Moons gravitationally influence each other
- Change the orbit shape

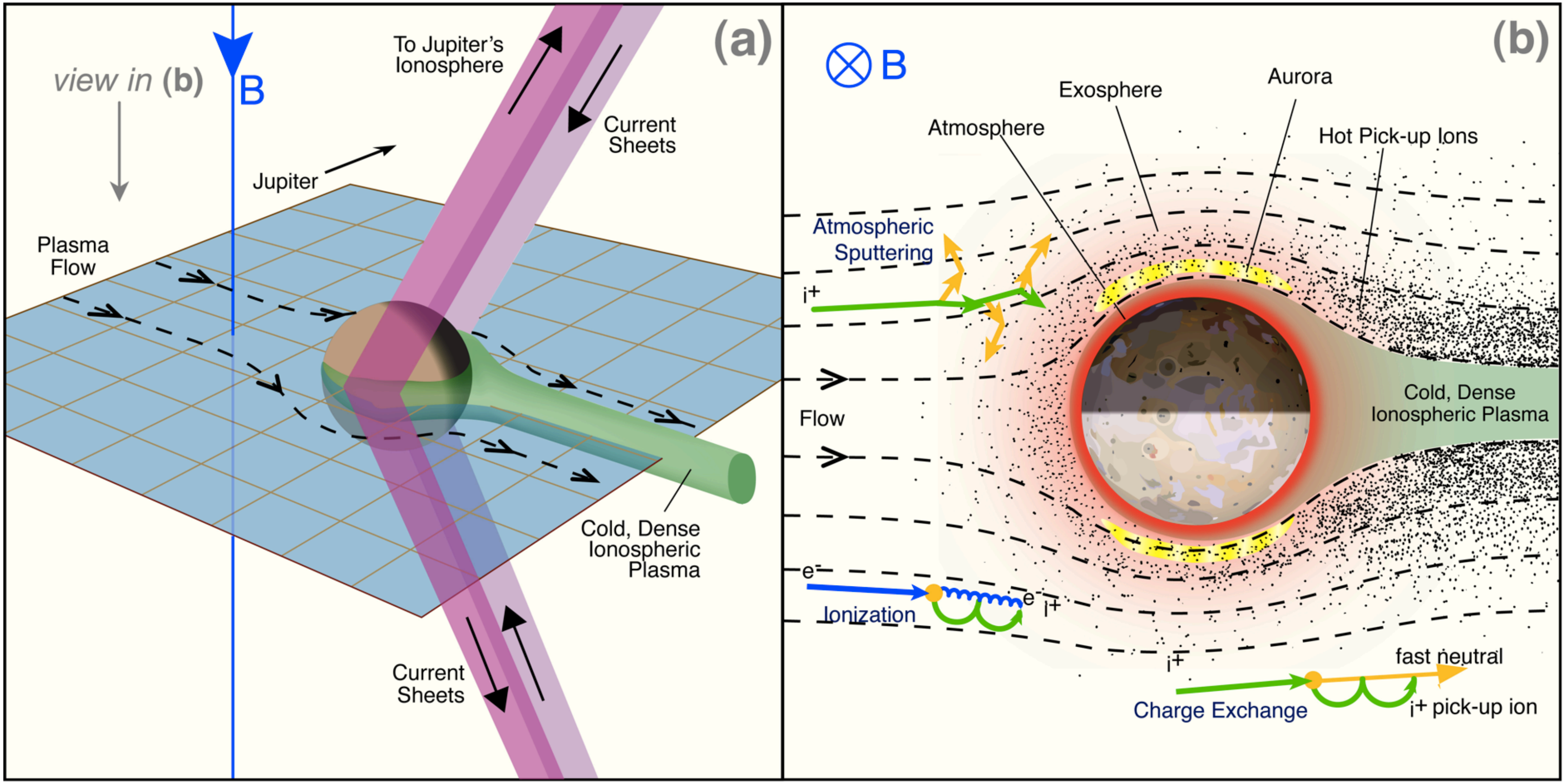
  circles → slight ellipses
- Io is tidally heated



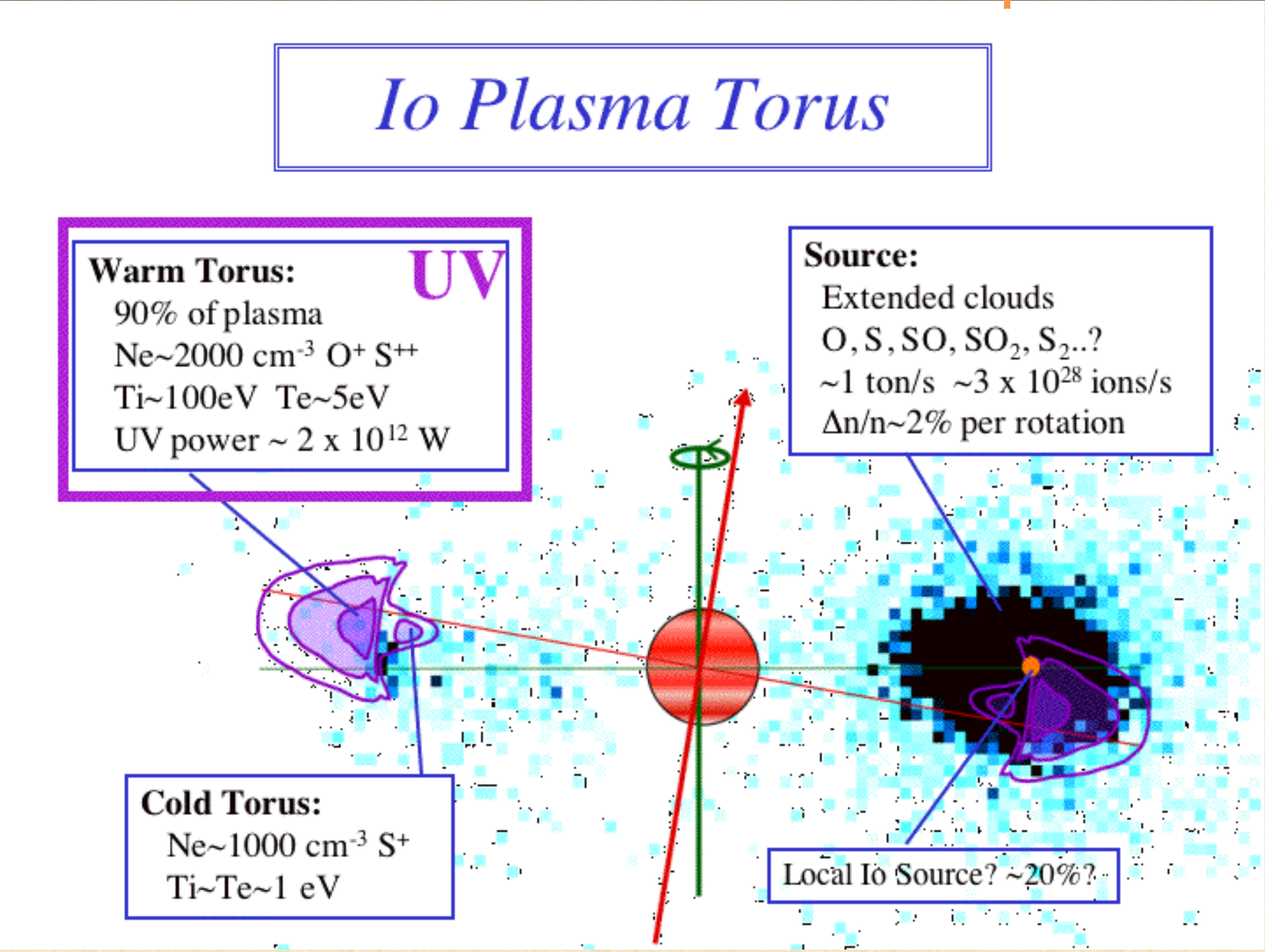
Volcanoes!

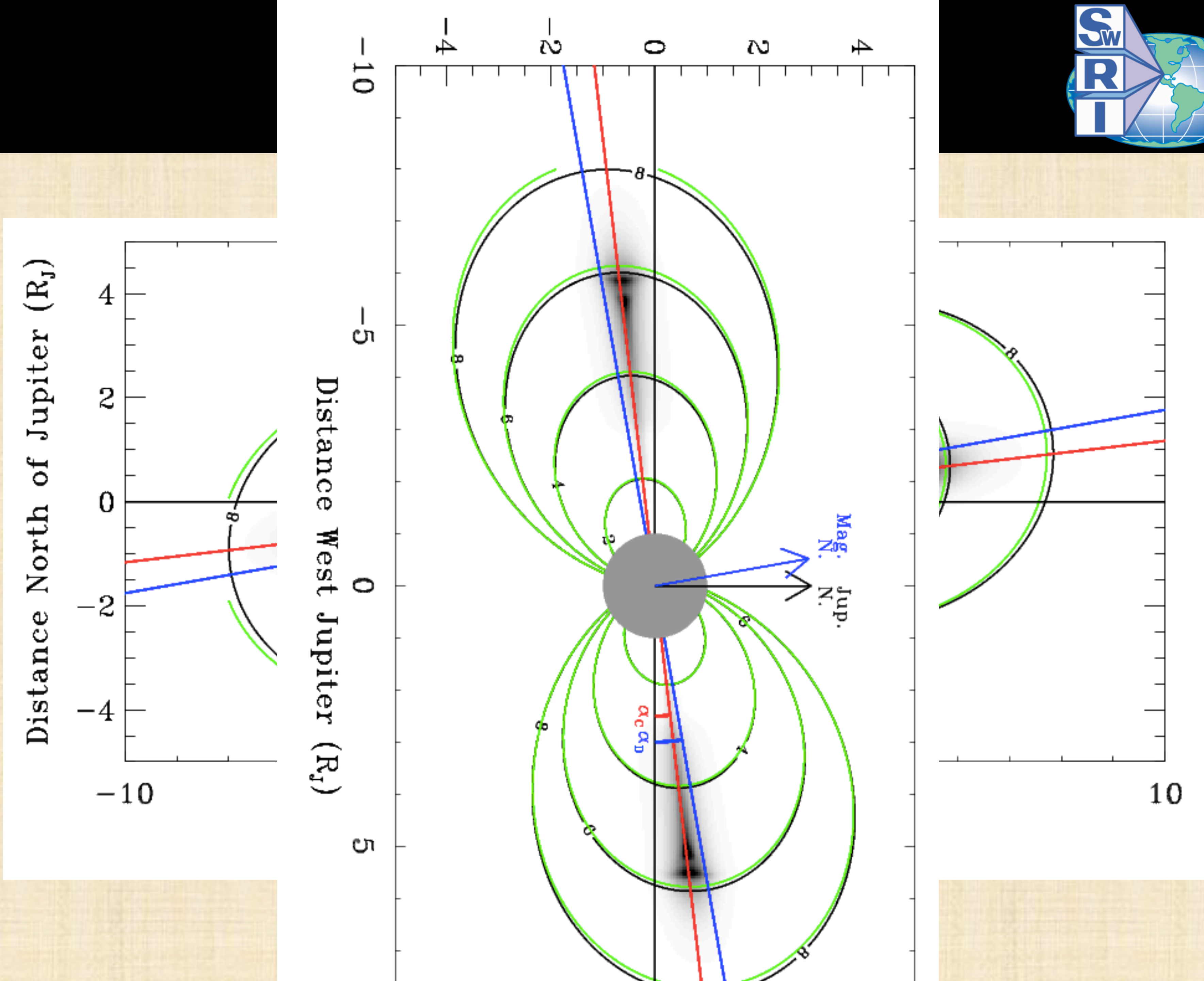


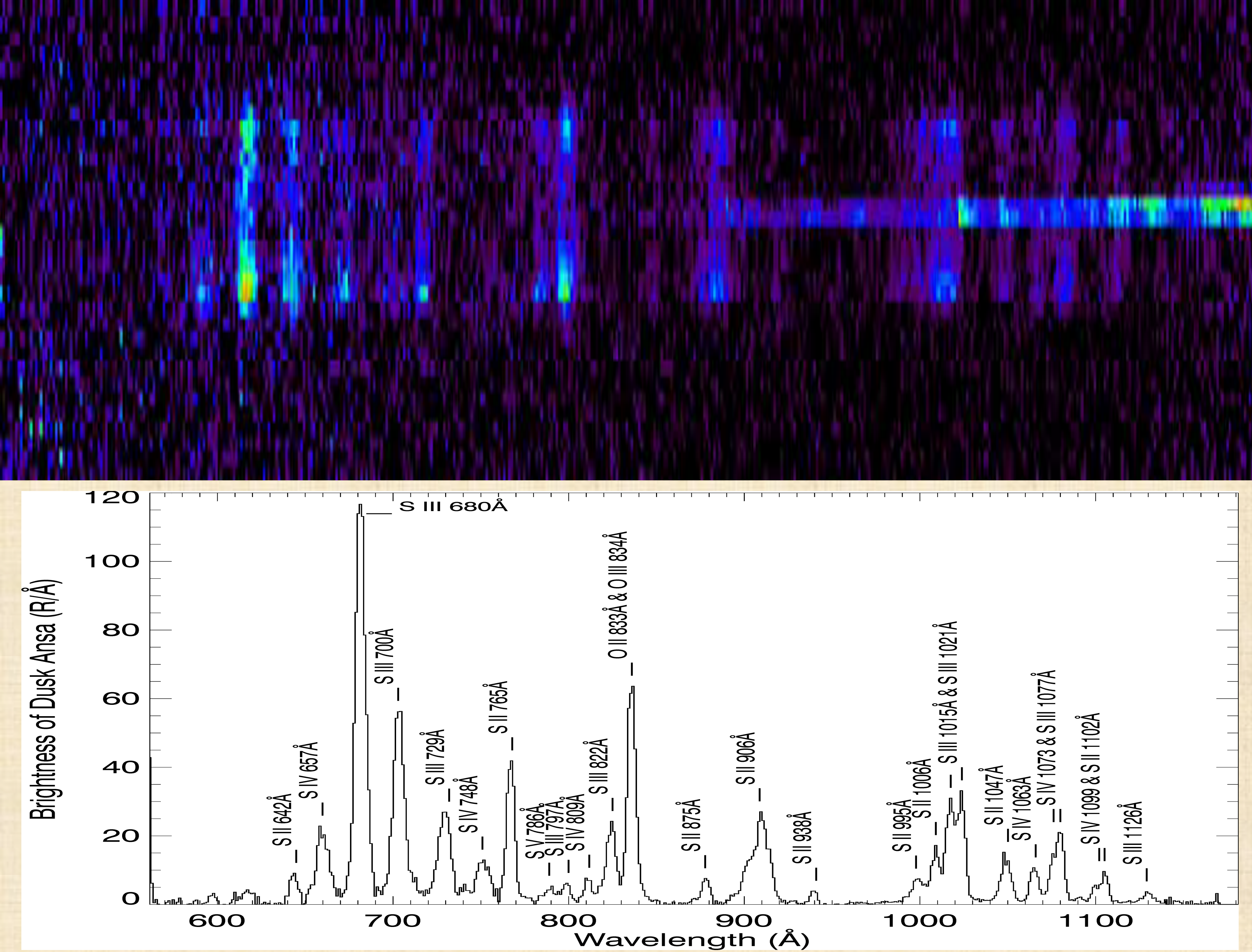
Loss Processes in Io's Atmosphere



Neutral atoms become ionized and form a toroidal cloud around Jupiter



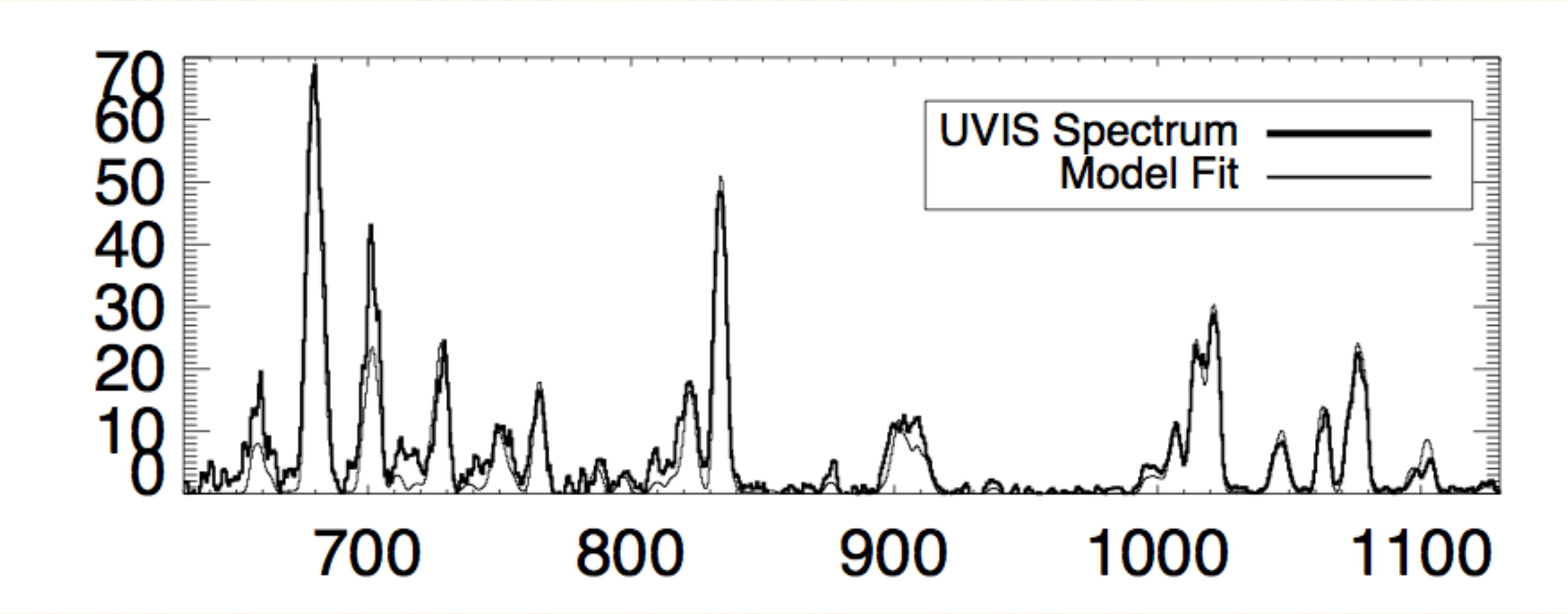

Distance North of Jupiter (R_J)
Distance West Jupiter (R_J)
Mag. N.
Jup. N.
α_C α_D
−10
10
−5
0
5
4
2
0
−2
−4
8
6
4
2



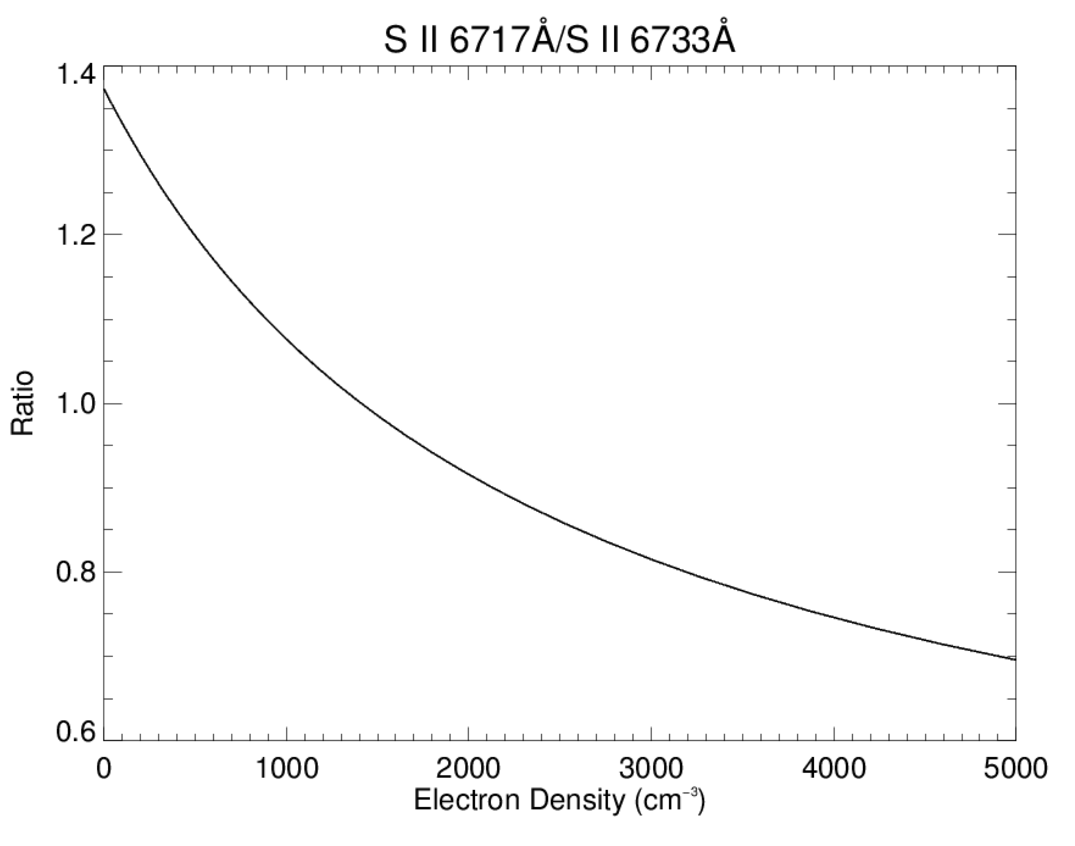
Brightness of Dusk Ansa (R/Å)
Wavelength (Å)
0
20
40
60
80
100
120
600
700
800
900
1000
1100
S III 680Å
S II 642Å
S IV 657Å
S III 700Å
S III 729Å
S IV 748Å
S II 765Å
S V 786Å
S III 797Å
S IV 809Å
S III 822Å
O II 833Å & O III 834Å
S II 875Å
S II 906Å
S II 938Å
S II 995Å
S II 1006Å
S III 1015Å & S III 1021Å
S II 1047Å
S IV 1063Å
S IV 1073 & S III 1077Å
S IV 1099 & S II 1102Å
S III 1126Å

Fits to Torus EUV Spectra

- As Yoshioka-san showed, we can accurately fit the EUV spectrum of the Io plasma torus and derive:
  - The ion composition in the torus (S^+, S^{2+}, S^{3+}, O^+, O^{2+})
  - The electron temperature
  - The total power emitted by the torus in the EUV



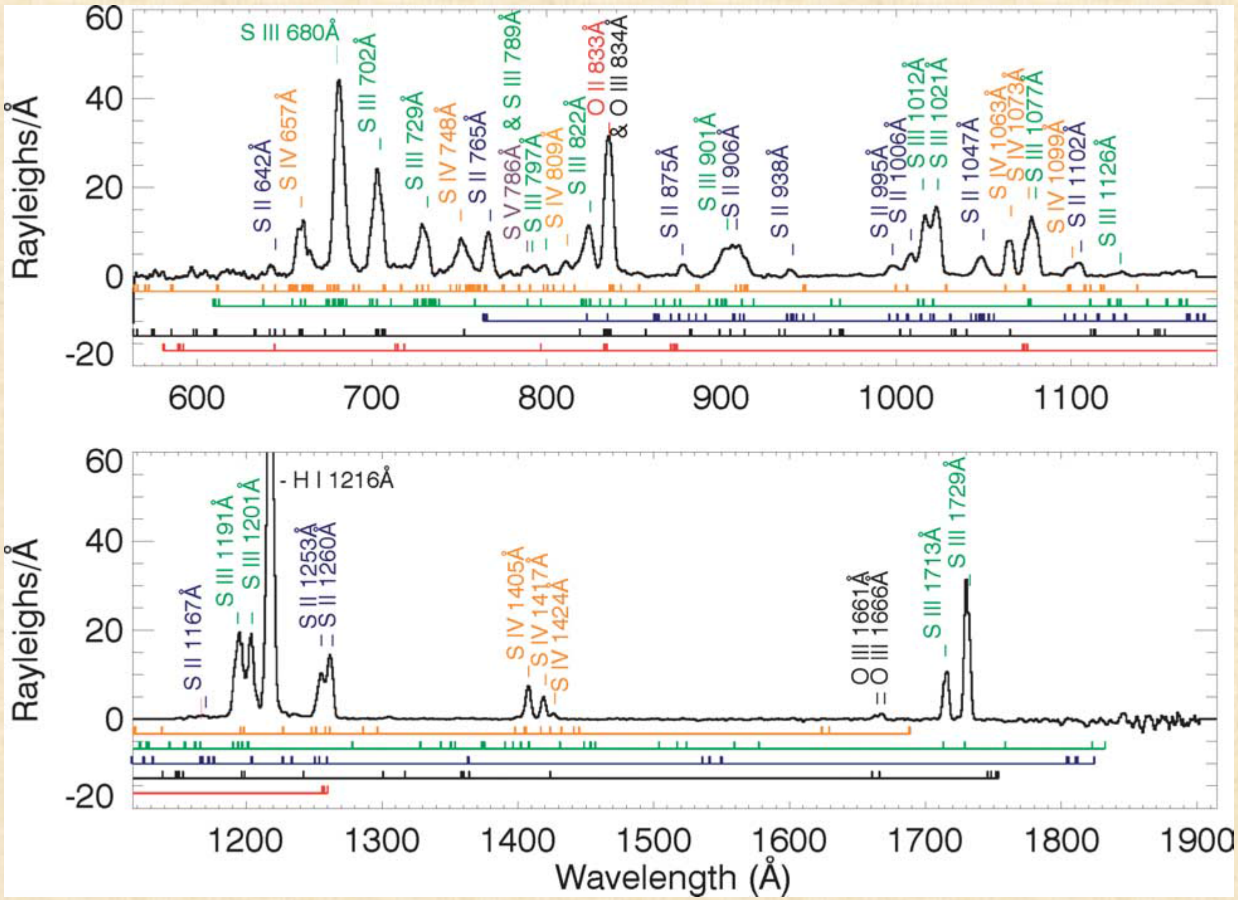
Why Observe the Io Torus From the Ground?



- The line ratio of S^+ 6713Å/S^+ 6731Å is a function of the local electron density
- None of the UV line ratios in the torus are sensitive to electron density

Why Observe the Io Torus From the Ground?

Cassini UVIS Spectrum of the Io Plasma Torus



- In the wavelength range of EXCEED, the only significant emission line of both O^+ and O^{++} overlap
- We have emission lines from O^+, S^+, and S^{++}, can determine O^+/S^{++} ratio

Joint HST/NOAO Proposal

- HST Cycle 20 proposal (February 2012)

  "A unique opportunity to discover how energy is transported through Jupiter's magnetosphere"

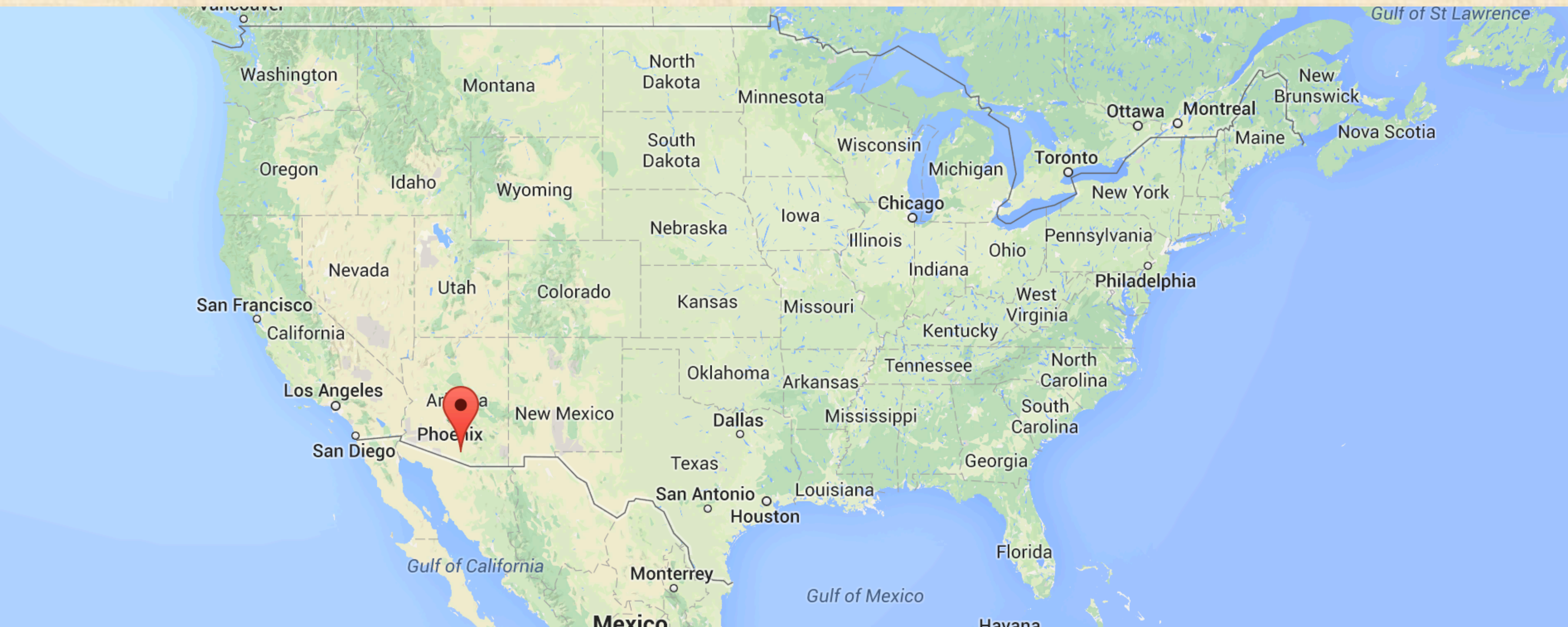
  – PI: S.V. Badman
- Requested 7 half nights of observing time on the 3.5m WIYN telescope on Kitt Peak
  – Obtain Io torus spectra with the SparsePak and Bench spectrographs
  – This requires blind tracking at non-sidereal rates
    - WIYN is not good at this!!!

Mayall 4m Telescope

- Completed in 1973
  - It was the 2nd largest telescope in the world!
- Significantly better blind tracking at non-sidereal rates than WIYN
- RC spectrograph (moderate resolution visible spectrograph)
  - OG 550 order-blocking filter
  - KPC-007 Grating
    - Tuned to 6500Å central wavelength; nominal 5500-7670Å range
    - 1.39Å/pixel; $\Delta\lambda$= 3.5Å resolution; R = 2000
- Observing time scheduled from 3-Jan-2014 to 9-Jan-2014
  - Kagitani & Steffl observing

Kitt Peak National Observatory

- KPNO founded in 1958
  - Operated by the National Optical Astronomical Observatories (NOAO)
- Largest concentration of optical telescopes in the world (22 separate telescopes from 0.5-4m)

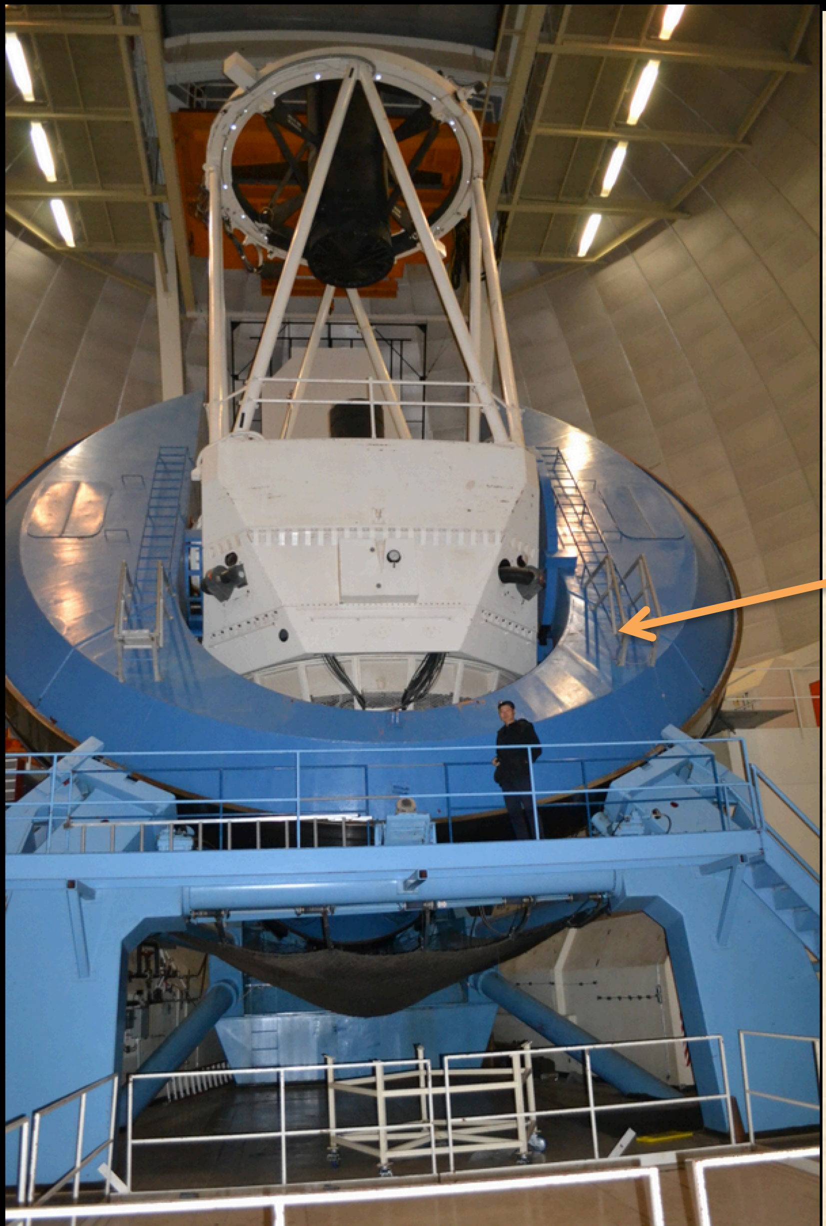


Kitt Peak National Observatory

The Mayall 4m telescope

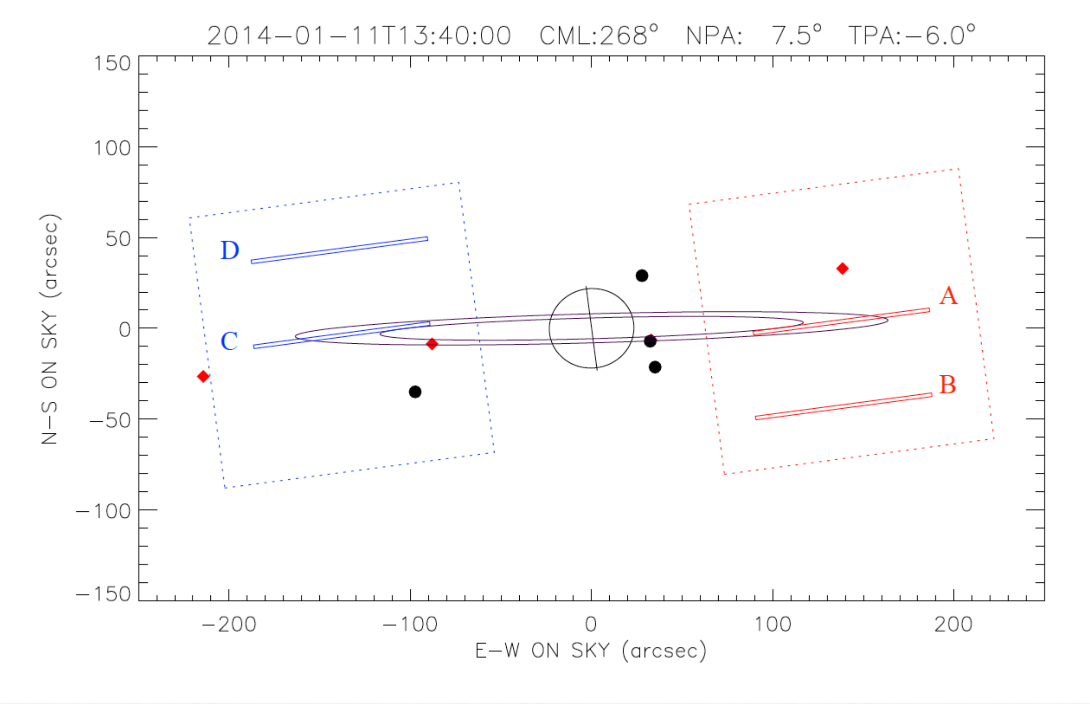
Minimum credit line: NOAO/AURA/NSF

Equatorial Mounted Telescope



Kagitani-san

Observing Strategy



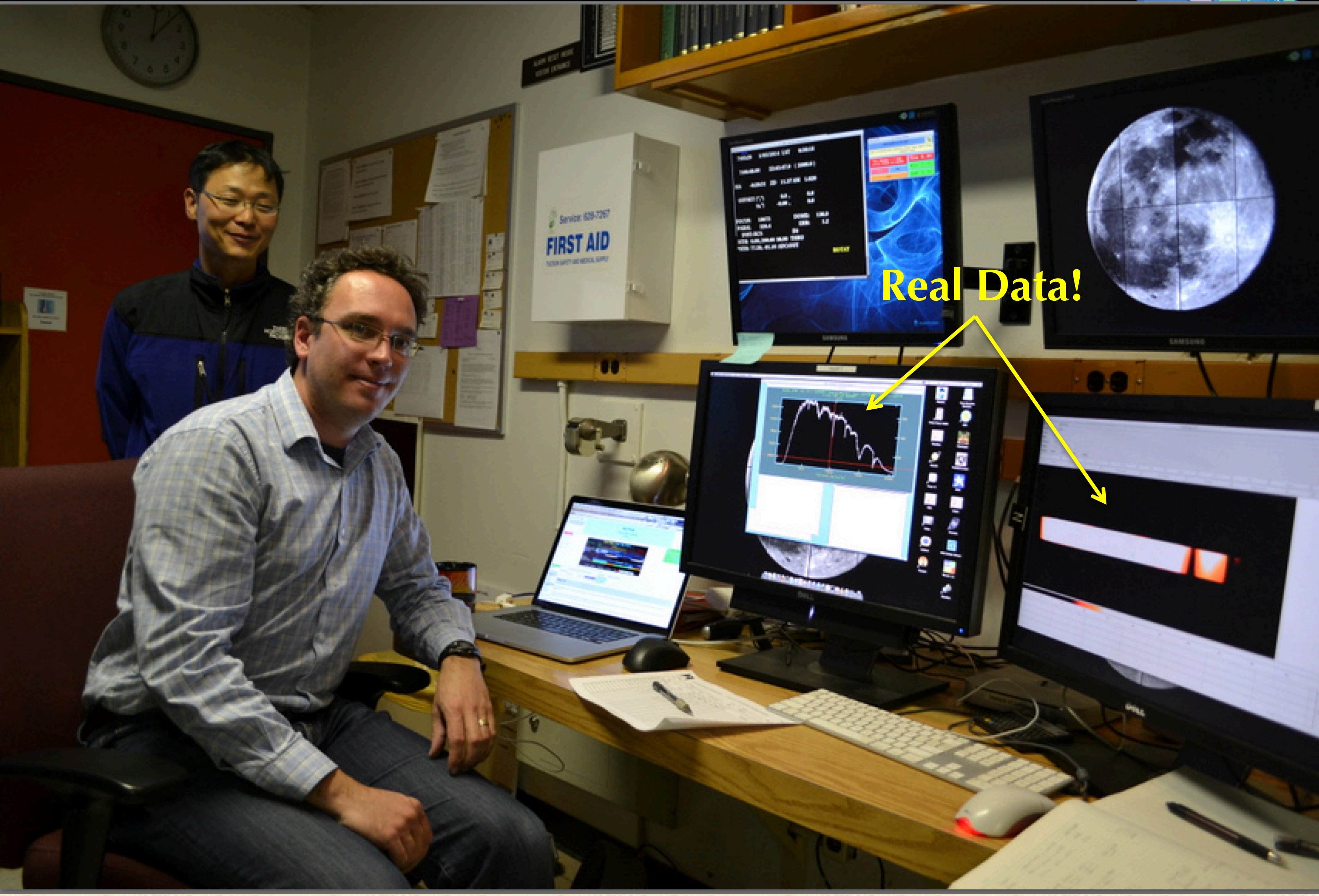
Point to Jupiter (absolute flux calibration)

Point to a Galilean satellite near the torus ansa of interest (pointing verification)

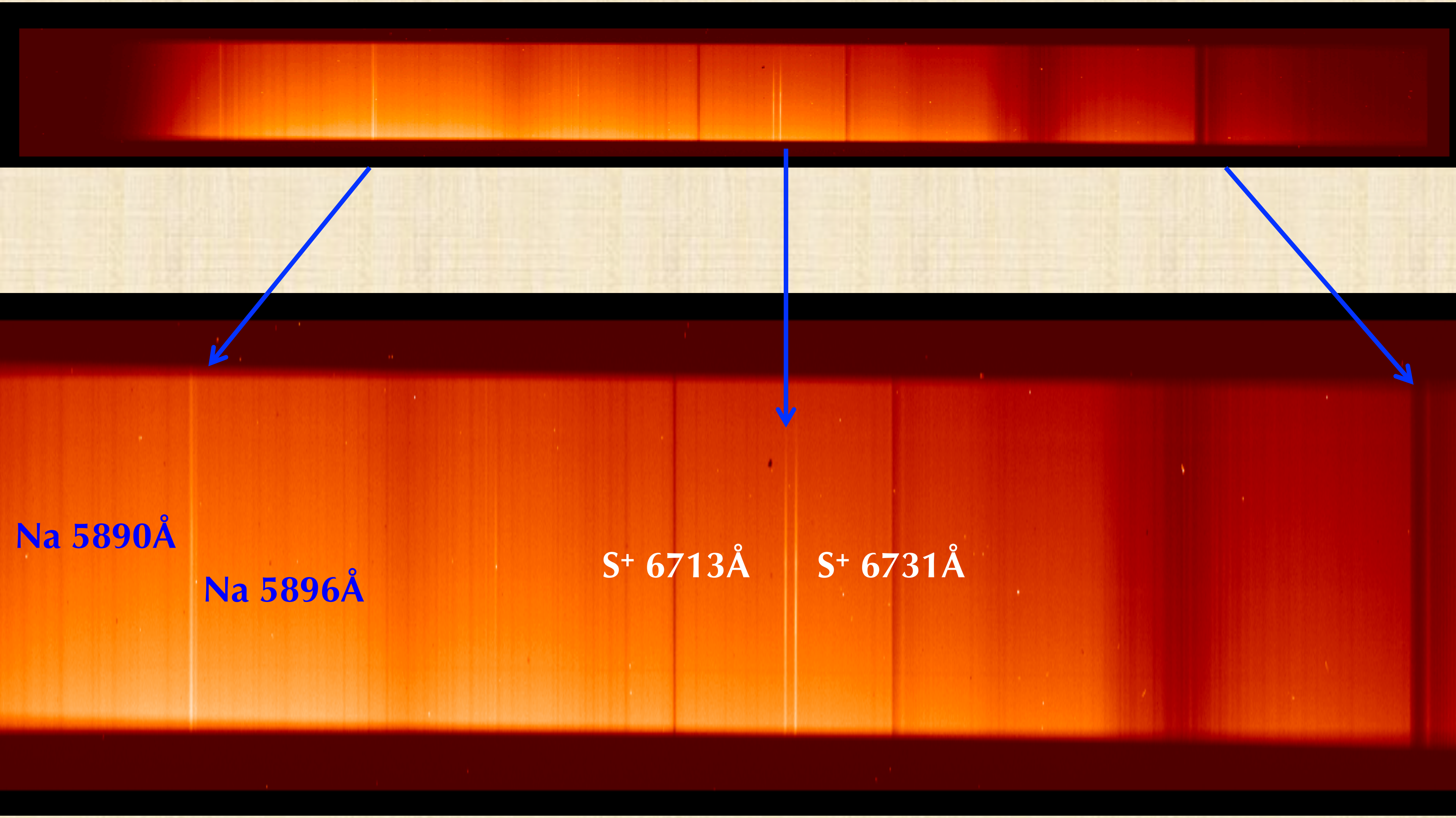
Obtain Torus spectra (positions A & C)

Obtain sky background spectra
(positions D&B)

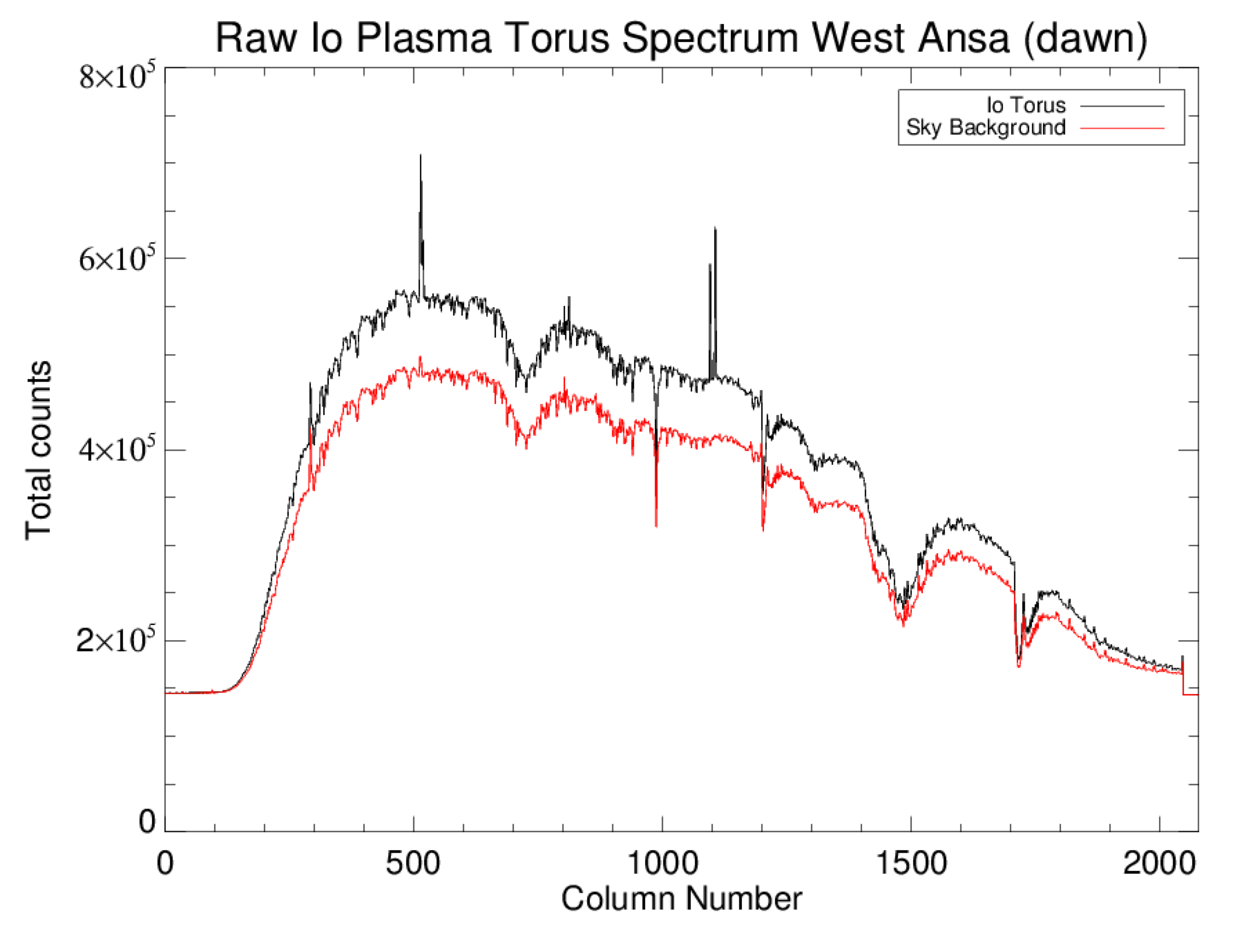
Rotate the slit to match the orientation of the torus


Real Data!
Service: 629-7267
FIRST AID

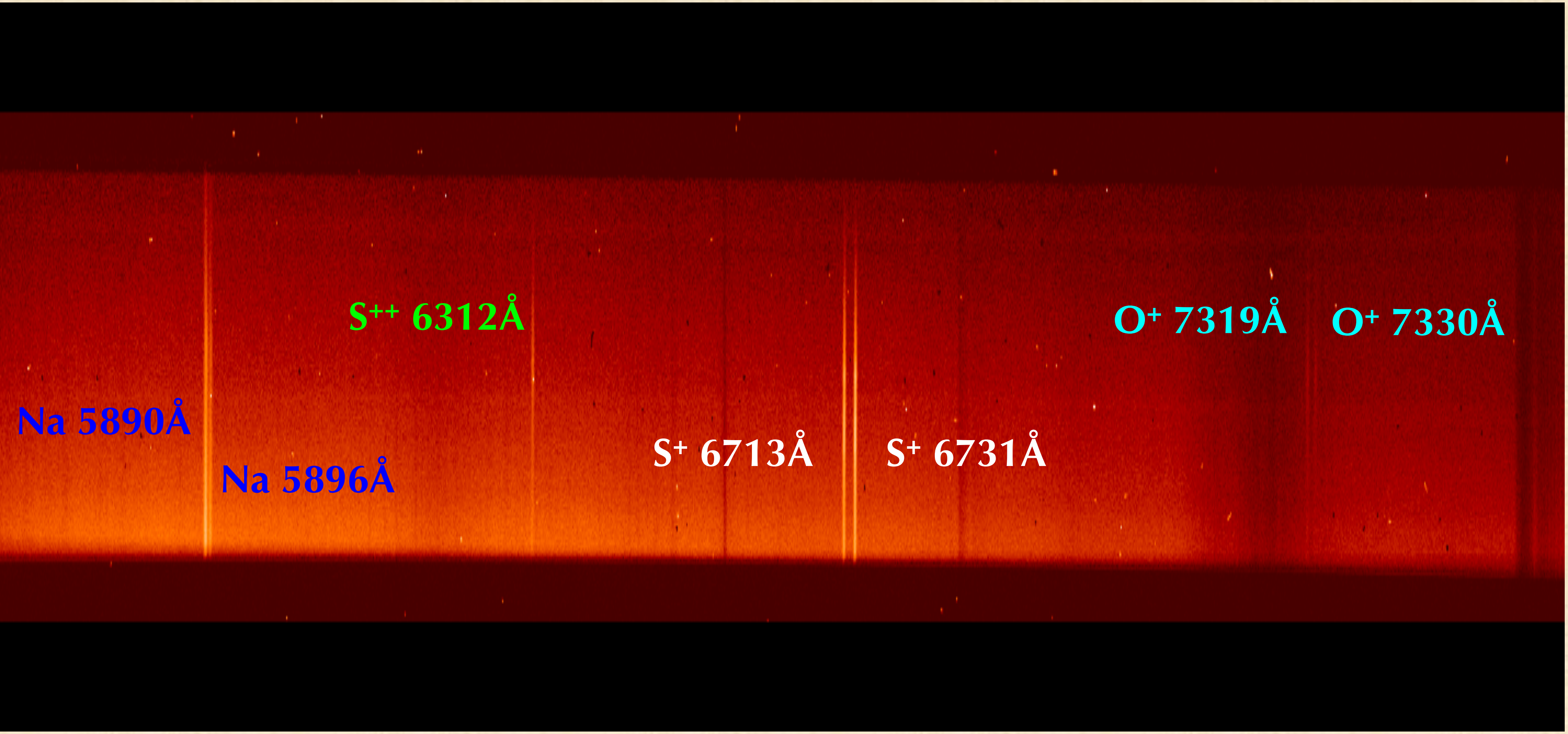
Raw Io Plasma Torus Spectrum



Spectra of the Torus



Rough Background-Subtracted Image (Preliminary!)



Conclusions from our Ground-Based Observing Run

- We have obtained ground-based optical wavelength spectra of the Io plasma torus using the Mayall 4m telescope on Kitt Peak
  - 7 half nights from Jan. 3, 2014 – Jan. 9, 2014
  - 4 good nights; 2 partially cloudy (Low S/N); 1 night lost to clouds
- From this data, we can measure the local electron density and the amount of O^+, relative to S^+ and S^{++}
  - Complimentary to EXCEED observations
- Other measurements that might be interesting:
  - Io's sodium clouds (Na 5890Å)
  - Spectra of the Galilean satellites
- Data analysis is ongoing!

Neutral Cloud Theory Models of the Io Plasma Torus

(What are the processes that produce the torus that we see?)

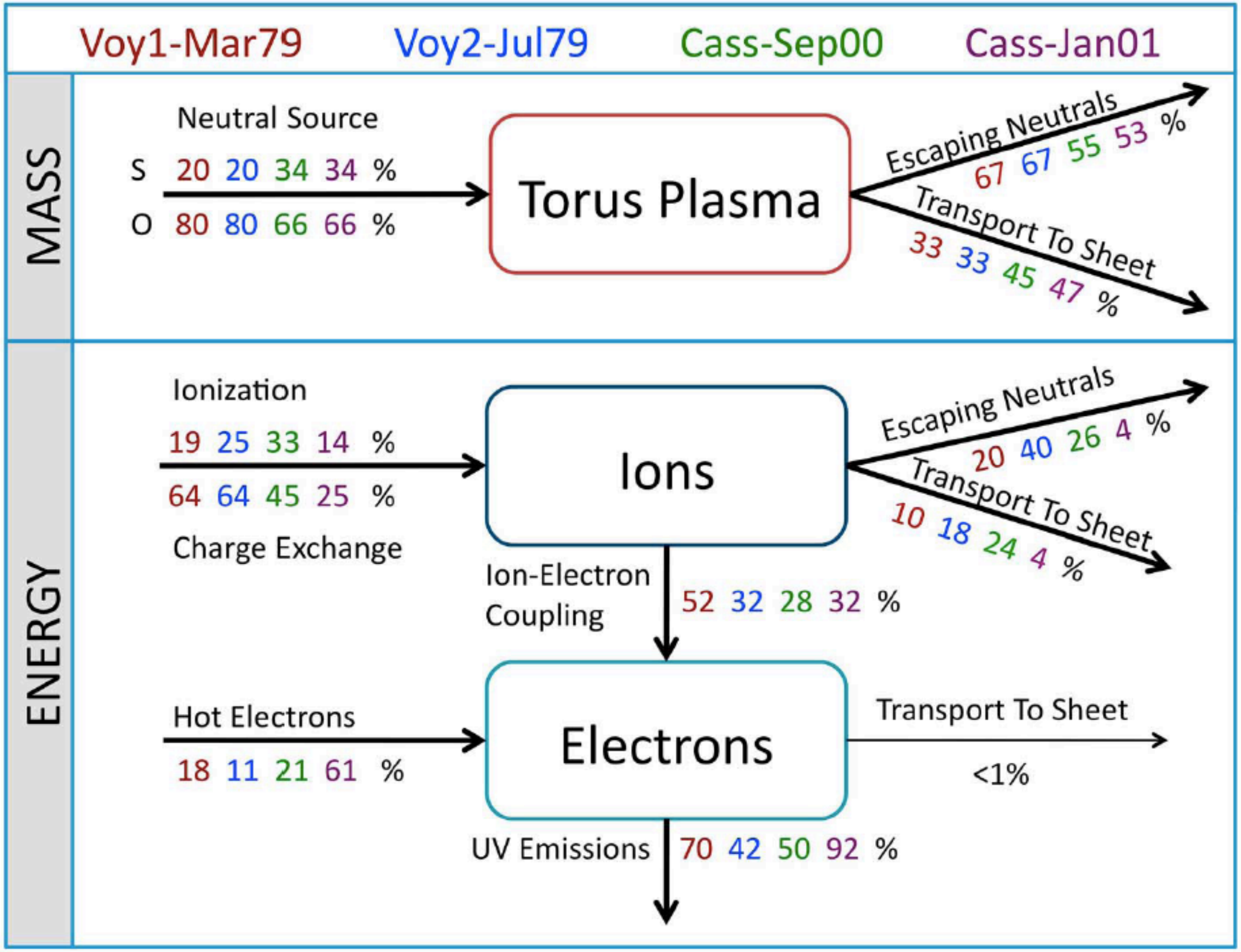
Neutral Cloud Theory

- Sources
  - Neutrals become ionized and are "picked up" by Jupiter's magnetic field
    - Both ionization and charge exchange reactions
    - S ions heated by 380 eV; O ions heated by 190 eV; electrons heated by ~0.006 eV
  - Electron heating
    - High energy tail to the electron distribution.
    - Necessary to provide UV-emitted power and match observed ionization state
- Sinks
  - Fast neutrals (charge exchange & recombination)
  - Radial transport (flux tube interchange; see talk by Hiraki-san)
  - Radiative Cooling
- Redistribution of energy
  - Ion-electron coupling
  - electron-electron thermal coupling

The Colorado Torus Model

- Input Parameters:
  - Neutral source rate
  - Ratio of oxygen to sulfur in the neutral source
  - Radial Transport timescale
  - Hot electron fraction
  - Hot electron temperature
- Output
  - Neutral and ion densities
  - Ion and thermal electron temperatures
  - Mass and energy flow

Mass and Energy Flow through the Io torus



The torus conditions seen by EXCEED are likely most similar to those of January 2001

Bagenal & Delamere (2010)

What happens to the torus when the neutral source increases?

- Density of neutrals increases
- Enhanced neutral ionization and pickup via charge exchange
  - More pickup energy added to the torus
- Electron temperature increases

Charge Exchange are very important and can produce counter-intuitive results!

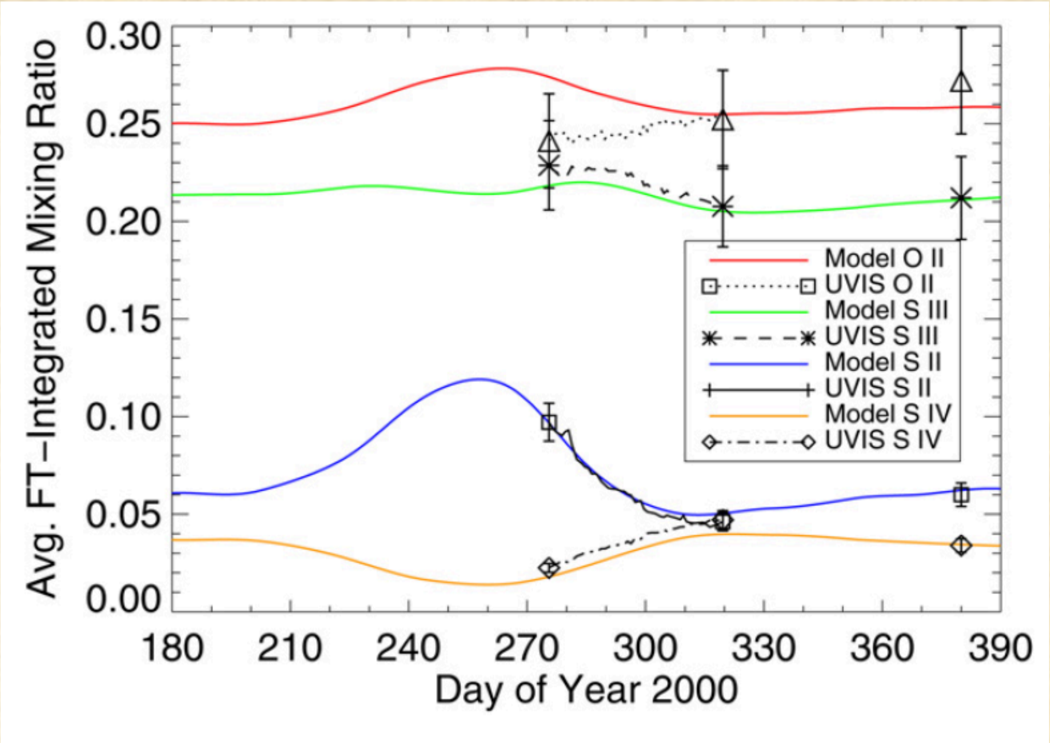
Table 2
Characteristic timescale of torus loss processes

Loss mechanism	S(I)	S(II)	S(III)	S(IV)	O(I)	O(II)	O(III)
Thermal e^- impact ionization	0.8	16.0	463	10400	6.4	926	70700
Hot e^- impact ionization	15.9	43.0	128	338	43.5	168	438
Recombination	–	1410	324	123	–	4050	1330
$S^+ + S^{2+} \rightarrow S^{2+} + S^+$	–	3.0	10.4	–	–	–	–
$S + S^+ \rightarrow S^+ + S^*$	5.0	85.2	–	–	–	–	–
$S + S^{2+} \rightarrow S^+ + S^+$	105	–	6240	–	–	–	–
$S + S^{2+} \rightarrow S^{2+} + S^*$	4.0	–	240	–	–	–	–
$S + S^{3+} \rightarrow S^+ + S^{2+}$	14.0	–	–	142	–	–	–
$O + O^+ \rightarrow O^+ + O^*$	–	–	–	–	2.6	43.3	–
$O + O^{2+} \rightarrow O^+ + O^+$	–	–	–	–	627	–	1070
$O + O^{2+} \rightarrow O^{2+} + O^*$	–	–	–	–	60.4	–	104
$O + S^+ \rightarrow O^+ + S^*$	–	8510	–	–	1990	–	–
$S + O^+ \rightarrow S^+ + O^*$	10.8	–	–	–	–	734	–
$S + O^{2+} \rightarrow S^+ + O^+$	13.9	–	–	–	–	–	95.7
$S + O^{2+} \rightarrow S^{2+} + O^+ + e^-$	20.1	–	–	–	–	–	138
$O + S^{2+} \rightarrow O^+ + S^+$	–	–	205	–	13.8	–	–
$O^{2+} + S^+ \rightarrow O^+ + S^{2+}$	–	262	–	–	–	–	105
$O + S^{3+} \rightarrow O^+ + S^{2+}$	–	–	–	24.4	9.6	–	–
$O^{2+} + S^{2+} \rightarrow O^+ + S^{3+}$	–	–	376	–	–	–	43.4
$S^{3+} + S^+ \rightarrow S^{2+} + S^{2+}$	–	585	–	346	–	–	–
Radial transport	–	62.0	62.0	62.0	–	62.0	62.0
Total of all loss processes	0.5	2.2	7.3	12.8	1.3	20.9	12.5

Note. Characteristic timescales given are for the "nominal" *Cassini* epoch torus composition and have been azimuthally averaged. All timescales have units of days.

What happens to the torus when the neutral source increases?

- The increased density of neutrals and singly charged species leads to more rapid loss of multiply ionized species like S^{3+} and O^{2+} through charge exchange reactions
- Although the electron temperature increases, the overall ionization state decreases!



Conclusions

- Neutral cloud theory (NCT) models can provide insight into the physical processes that produce the Io torus
- NCT models must be constrained by observations to be useful
- The Io torus parameters derived from the EXCEED observations (ion composition, electron temperature, total emitted power) provide excellent constraints on neutral cloud models

Charge Exchange Reactions are very important

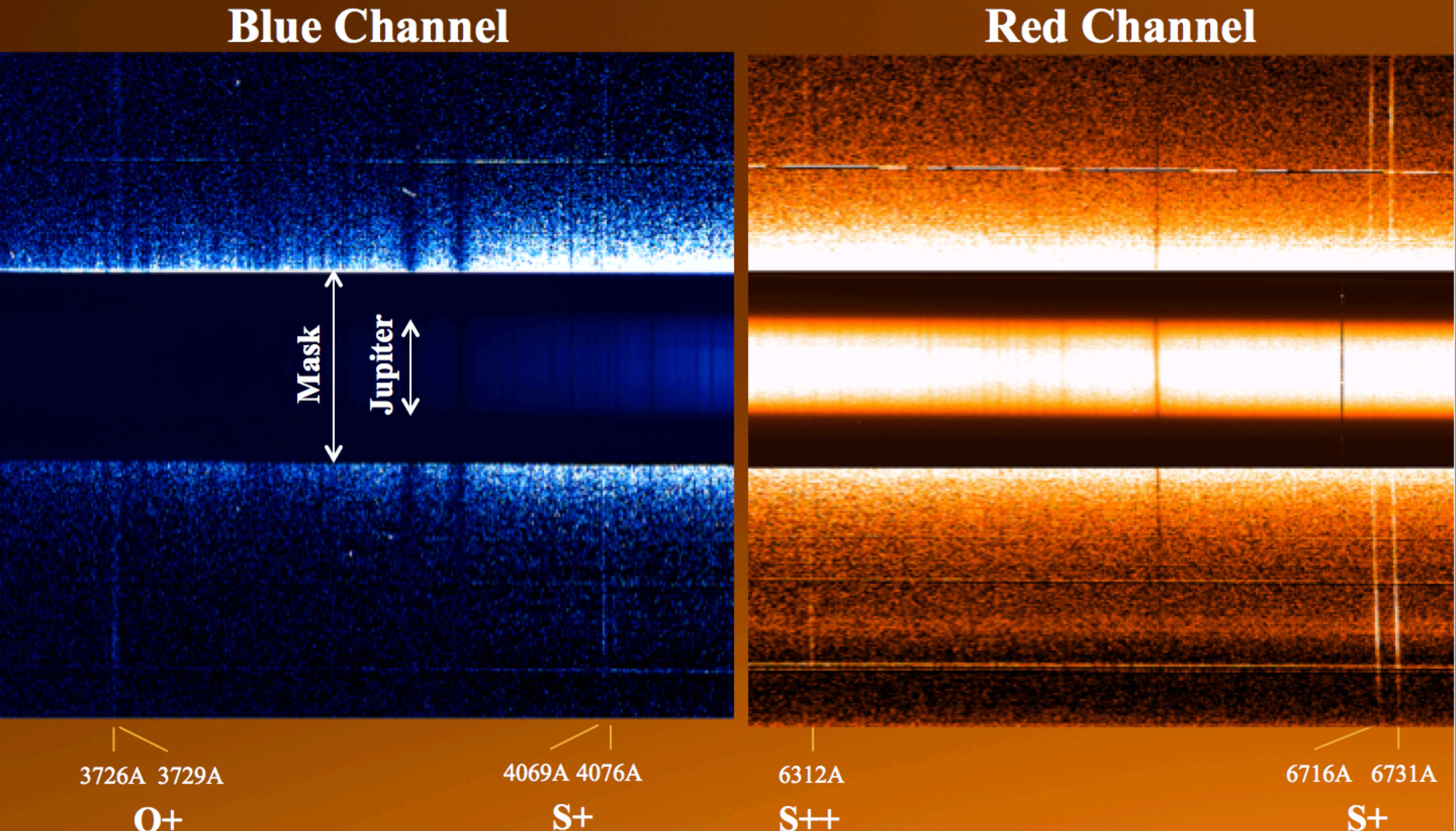
Table 1. Charge Exchange Reactions, $L = 6.0$, k_0 [*Smith and Strobel*, 1985], k_1–k_{16} [*McGrath and Johnson*, 1989]

Reaction	k, $cm^3 s^{-1}$
$S^+ + S^{++} \rightarrow S^{++} + S^+$	$k_0 = 8.1 \times 10^{-9}$
$S + S^+ \rightarrow S^+ + S$	$k_1 = 2.4 \times 10^{-8}$
$S + S^{++} \rightarrow S^+ + S^+$	$k_2 = 3 \times 10^{-10}$
$S + S^{++} \rightarrow S^{++} + S$	$k_3 = 7.8 \times 10^{-9}$
$S + S^{+++} \rightarrow S^+ + S^{++}$	$k_4 = 1.32 \times 10^{-8}$
$O + O^+ \rightarrow O^+ + O$	$k_5 = 1.32 \times 10^{-8}$
$O + O^{++} \rightarrow O^+ + O^+$	$k_6 = 5.2 \times 10^{-10}$
$O + O^{++} \rightarrow O^{++} + O$	$k_7 = 5.4 \times 10^{-9}$
$O + S^+ \rightarrow O^+ + S$	$k_8 = 6 \times 10^{-11}$
$S + O^+ \rightarrow S^+ + O$	$k_9 = 3.1 \times 10^{-9}$
$S + O^{++} \rightarrow S^+ + O^+$	$k_{10} = 2.34 \times 10^{-8}$
$S + O^{++} \rightarrow S^{++} + O^+ + e^-$	$k_{11} = 1.62 \times 10^{-8}$
$O + S^{++} \rightarrow O^+ + S^+$	$k_{12} = 2.3 \times 10^{-9}$
$O^{++} + S^+ \rightarrow O^+ + S^{++}$	$k_{13} = 1.4 \times 10^{-9}$
$O + S^{+++} \rightarrow O^+ + S^{++}$	$k_{14} = 1.92 \times 10^{-8}$
$O^{++} + S^{++} \rightarrow O^+ + S^{+++}$	$k_{15} = 9 \times 10^{-10}$
$S^{+++} + S^+ \rightarrow S^{++} + S^{++}$	$k_{16} = 3.6 \times 10^{-10}$

Coordinated Io Torus observations from Apache Point Observatory

Apache Peak Observatory (APO)
ARC 3.5m telescope

Torus Spectrum from Apache Point Obs.



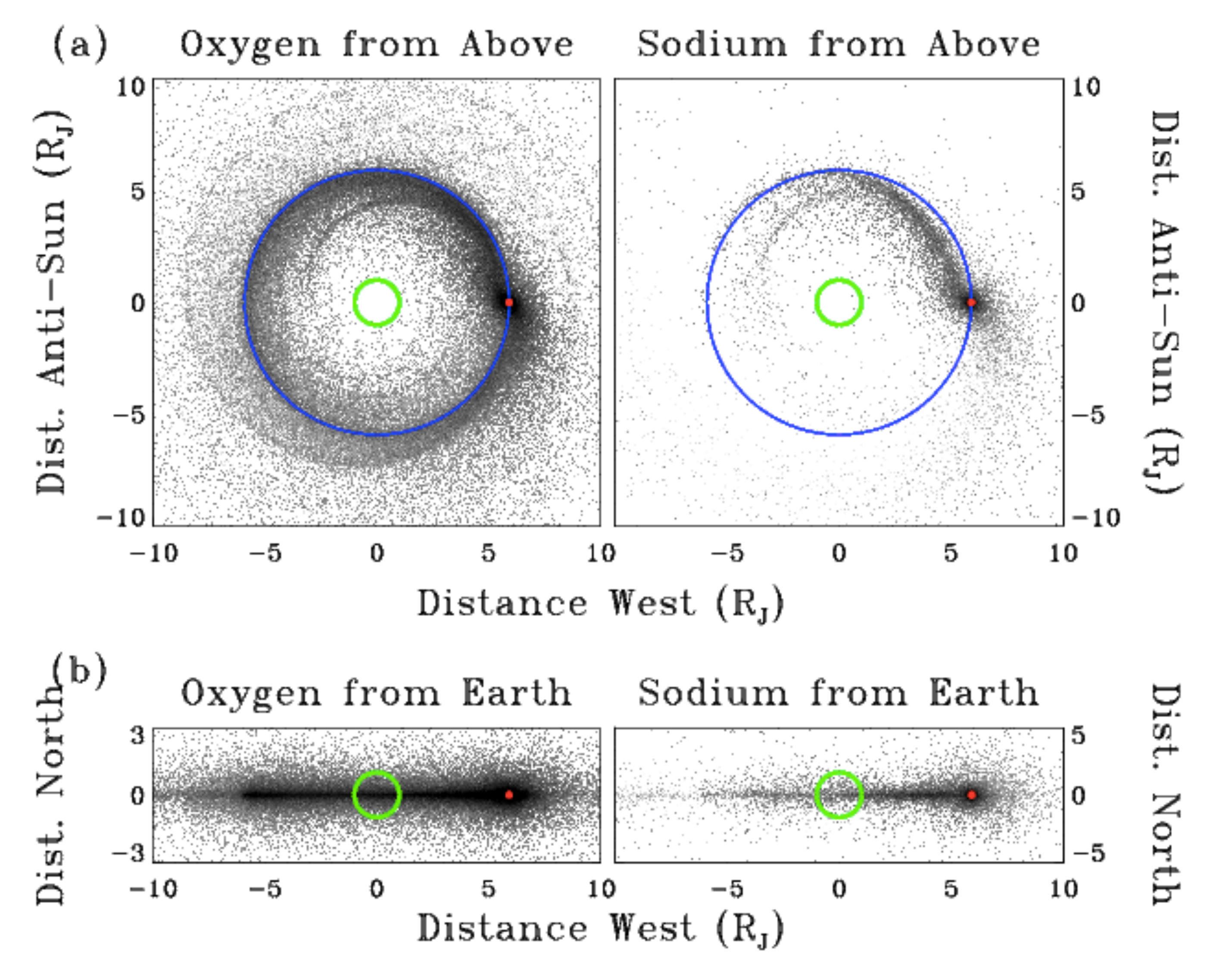
10 min exposure - Jan 7 UT

Apache Point Observatory Campaign

- Torus-aligned slit spectroscopy at ~15 min cadence
- Vertical slit measures $T_{||}$ anisotropies from ion scale heights.
- 0.6 Angstrom / pixel resolution. 0.9” slit width.
- Dual red and blue optical channels, S^+, S^{++}, O^+ and Na emissions
- Jupiter in field – simple pointing, calibration standard

Data in hand	Observations Scheduled
Nov 07	Feb 06
Nov 09	Feb 08
Dec 17	Feb 13
Dec 24	Feb 15
Jan 07	Feb 18

→ Reduction pipeline in progress.



(a)
Oxygen from Above
Sodium from Above
Dist. Anti–Sun (RJ)
Distance West (RJ)
(b)
Oxygen from Earth
Sodium from Earth
Dist. North
Distance West (RJ)

Burger (2006)