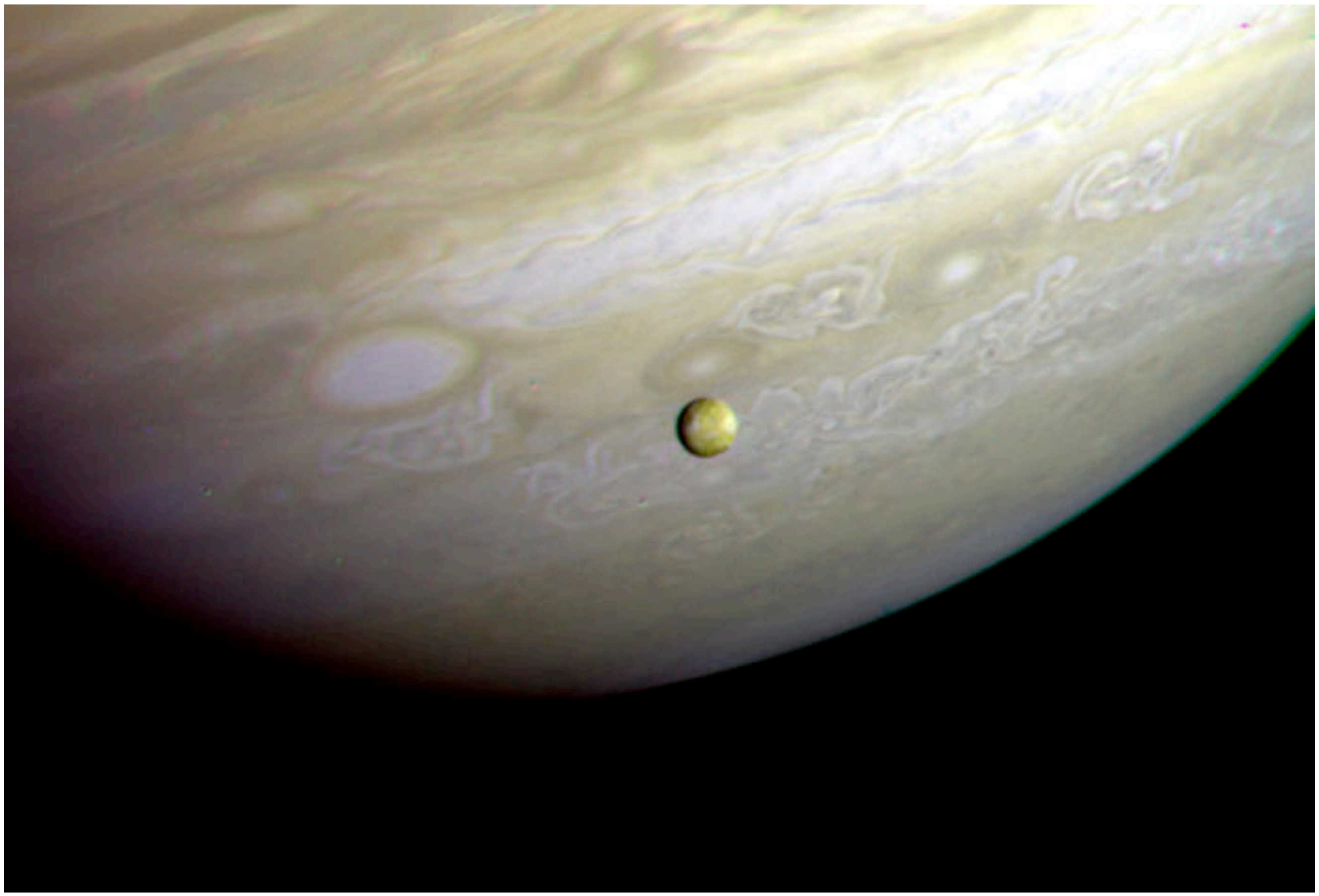
Io`s Neutral Atmosphere



Io`s Basic Statistics:

Mass:	9 x 10^{25} g (0.015 Earth Mass)
Radius:	1800 km (1.1 Moon Radii)
Density:	3.53 g/cm^3 (90% Mars` Density)
Composition:	Iron-Silicate Core: Sulfur-Alkali-Oxygen Surface:
Orbital Radius:	4.25 x 10^5 km (1.1 Moon-Earth Distance)
Orbital Period:	1.77 days
Surface Temperature:	~130 K
Escape Velocity:	2.2 km/sec

Some History:

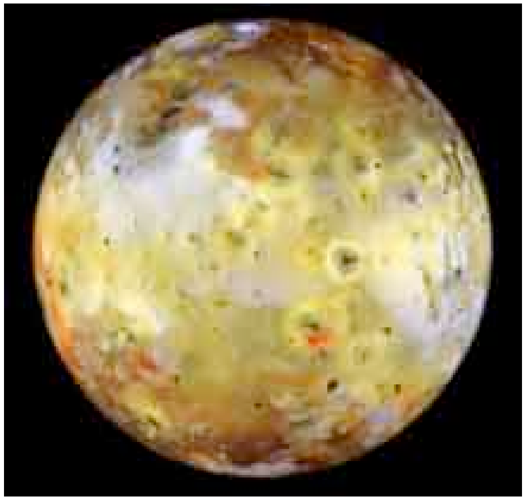
Io was the first Jupiter satellite to be suspected of having an atmosphere.

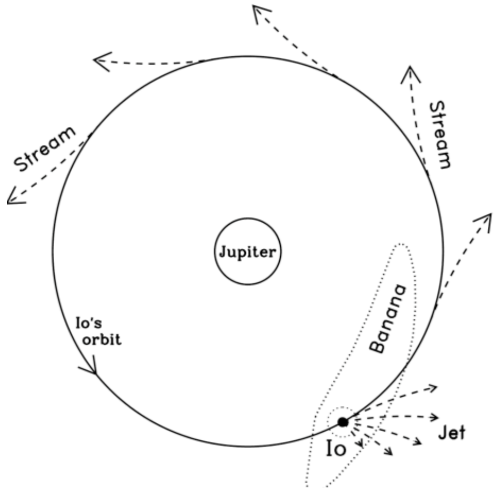
1) Pioneer 10 measured an ionosphere (Kliore et al 1974) with a peak density of about 60000 e^-/cm^3.

2) Brown (1975) discovers the presence of a cloud of Na in the vicinity of Io. Within a year a similar K cloud is discovered. Non-thermal velocities assumed.

3) Kupo (1976) discovers the Io plasma Torus.

First models assume that torus ions sputter an atmosphere off the surface of Io. The Na and K are not volatile enough for another known mechanism.





Early atmospheric models suggest compositions similar to comets, with NH_3, CO, CH_4, and Ne

Some History:

In 1979 Voyager 2 discovers volcanism on Io.

1) Over 100 sites of active volcanism are ultimately discovered.

2) Outflow velocities of 0.5 km/sec are measured.

3) SO_2 identified both as a solid frost and as a gas (hotter than expected).

4) Sulfur ions found in both torus and Jovian atmosphere.

5) Io resurfaced at a rate of about 0.2 mm/year (1 km in 5×10^6 yr).

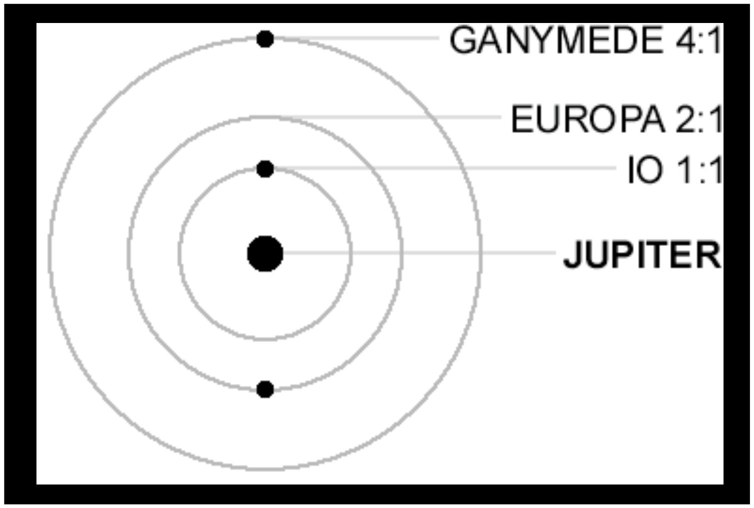
Icy models discarded. SO_2 now the primary constituent. Assumed to be in thermodynamic equilibrium and hydrostatic (gravity-pressure) equilibrium.

The Road Less Traveled:

The energy source for the volcanoes is identified as tides. This had never been considered.

Tides

Io, Europa, and Ganymede are in a unique 1:2:4 orbital (Laplace) resonance, where they all pull on each other in a repetitive manner.



Io gets the worst of this.

Basic Result?

1) Io is the densest object in the outer solar system (past Mars).

2) Io has the lowest water content of any outer solar system object and may be the driest object in the solar system.

Tidal Geology:

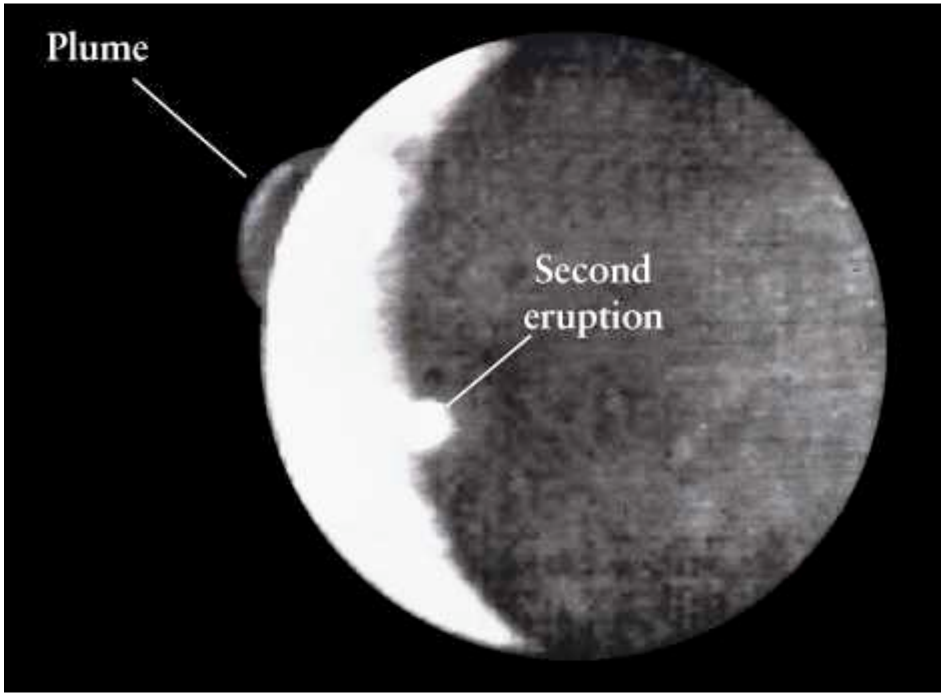
Tidal energy deposition.

The estimated tidal energy put into Io is ~10^{14} ergs/sec (500x tidal energy of the Earth/area).

Io cannot dissipate this energy except through volcanic activity!

There are more than 100 active calderas on Io at any given time.

Temperatures range from 300 to more than 2000 K in these regions.

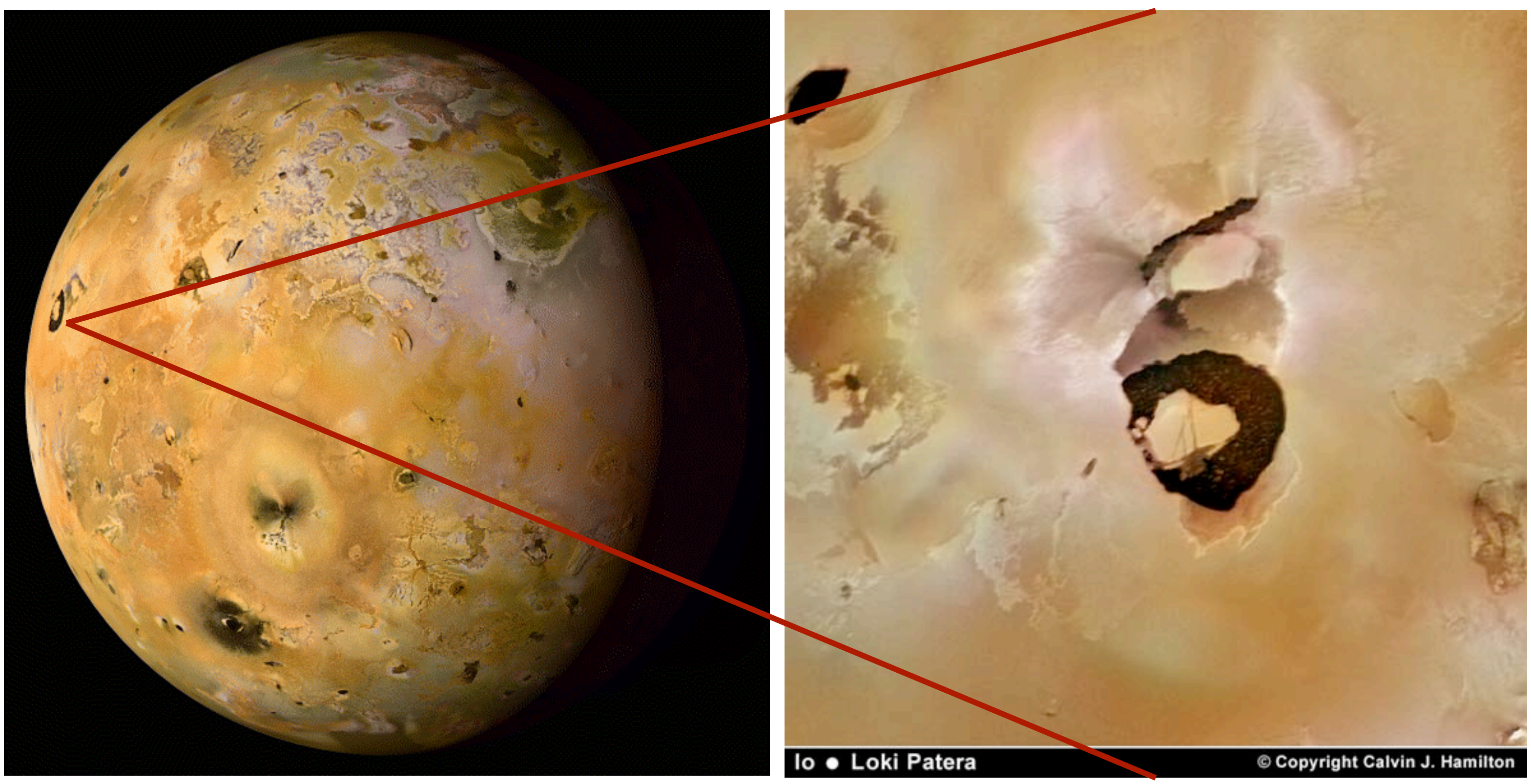


The Surface Atmosphere and Volcanoes:

Io`s volcanos eject several x10^3 tons/sec of material onto its surface and atmosphere.

The ejecta is composed of compounds containing SO, NaCl, S, O, O_2, and SO_2.

Sublimation and Volcanic activity suggest variations in density.



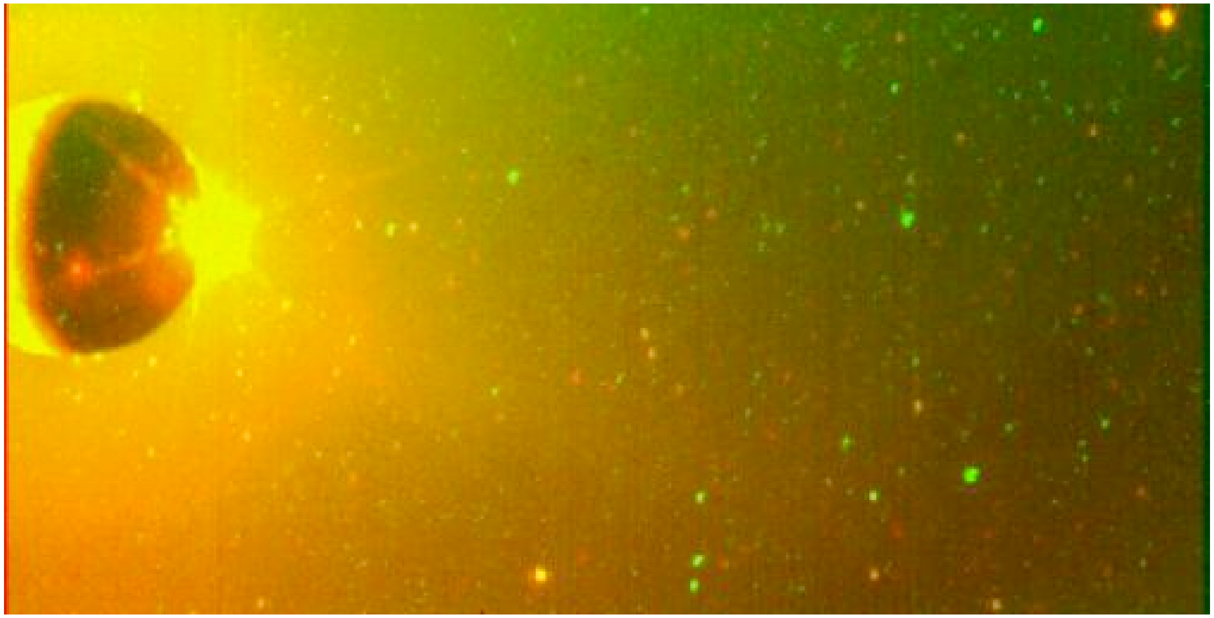
The SO_2 Atmosphere:

SO_2 is assumed to be the major component of the atmosphere.

1) Global averages have column densities of ~$10^{16}/cm^2$.

2) There is a slight asymmetry in the leading vs. trailing hemispheres with the trailing being hotter and denser (sputtering?)

3) Much of the surface is covered by SO^2 which supports nbar pressures at 130K (blackbody) temperatures (sublimation?)

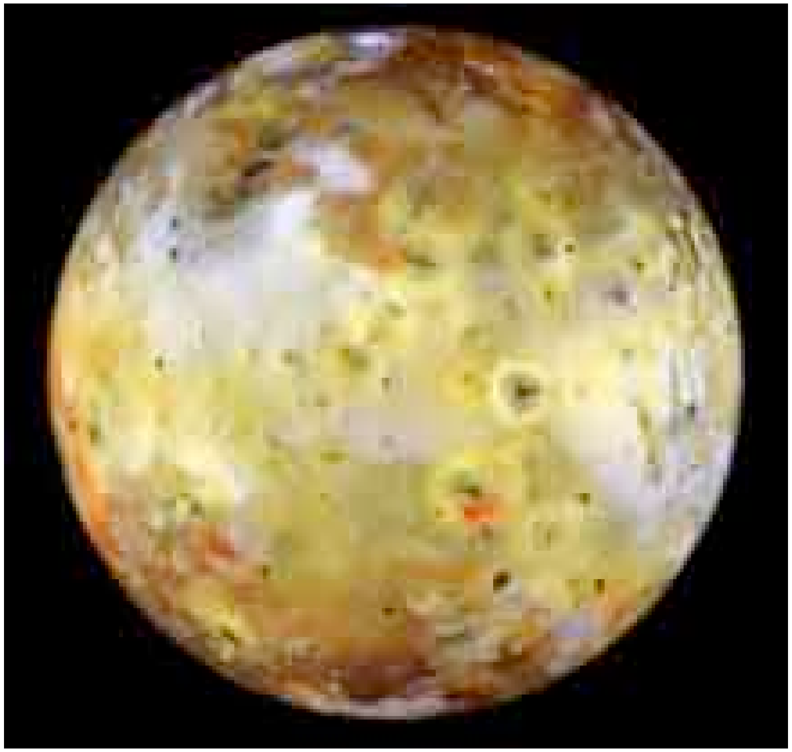


Open Questions after Voyager

How extended was the atmosphere across the surface?

Volcanic plumes contribute lots of material. Is this the atmosphere or the source of frost from which an atmosphere forms?

What role does sublimation have? How does the atmosphere vary wrt to the subsolar point?



What other species are present?

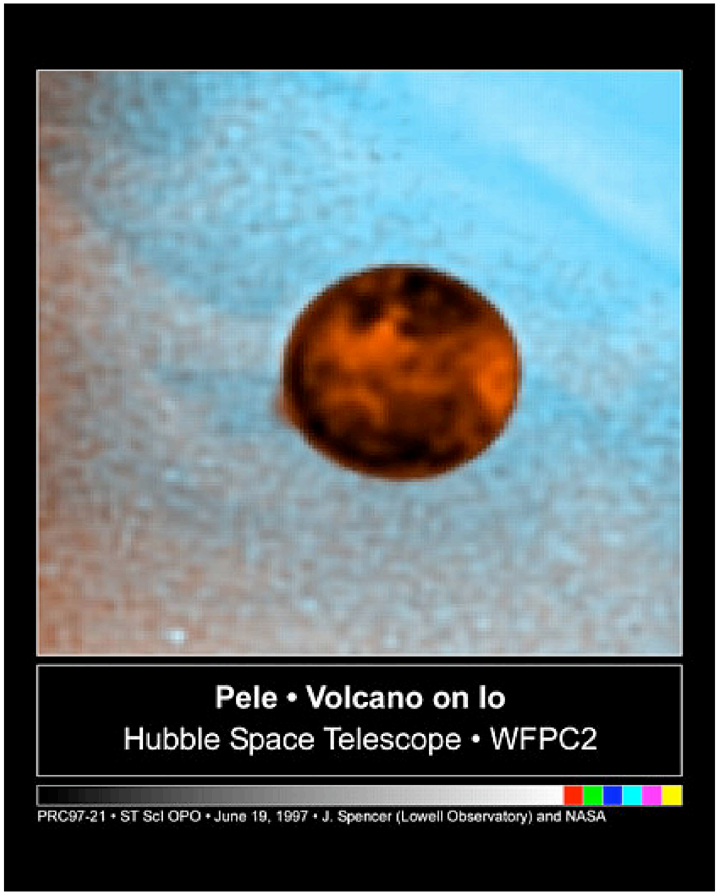
What variability does it have?

How well mixed is the atmosphere with altitude and location?

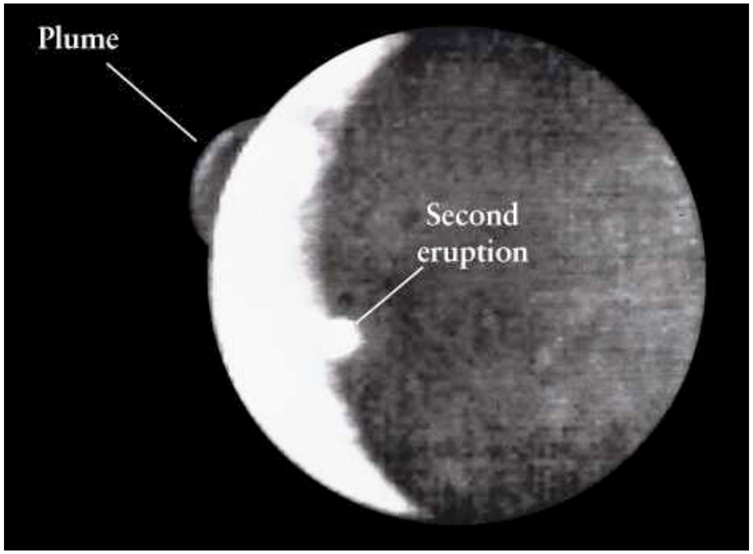
The Plumes

Studies of the plumes against the disk of Jupiter suggest a thick column of dust or SO_2 (Spencer et al.1997)

Spectro-imaging in 2000 (Spencer et al 2000) show unstable S_2 as well. Reduces the required SO_2 density.



Pele plume (correcte for S_2) ends up with a column of about $10^{16}/cm^2$ (global average).



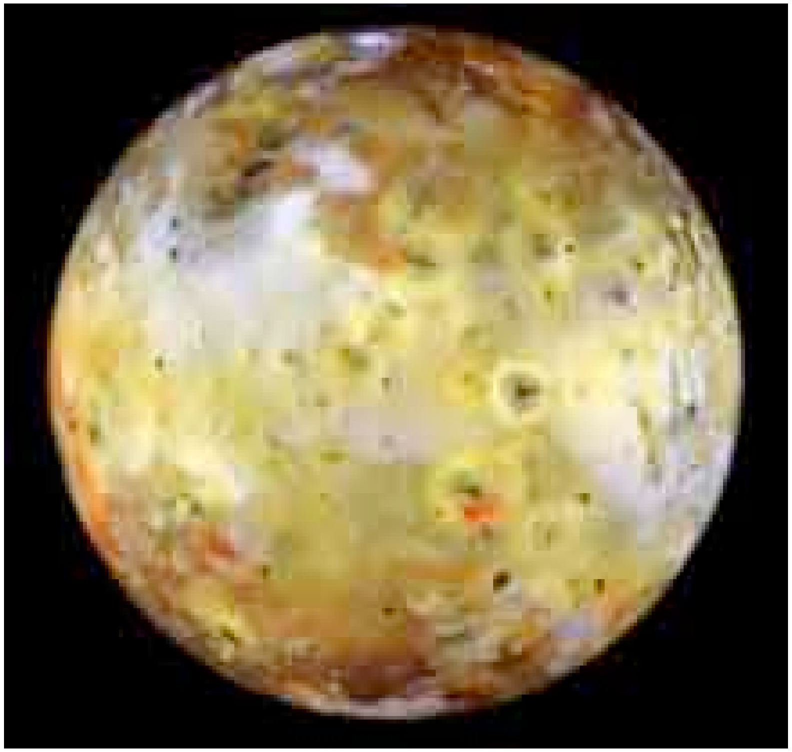
Spatially Variable Measurements

McGrath et al. (2000) perform 3 measurements at different locations on the surface (a plume region, a high-frost region, and a low frost region).

Shows that the atmosphere is somewhat global (everyplace had a gas column.

However the atmosphere is patchy.

Range in columns is 0.7-3.25 $x10^{16}/cm^2$.



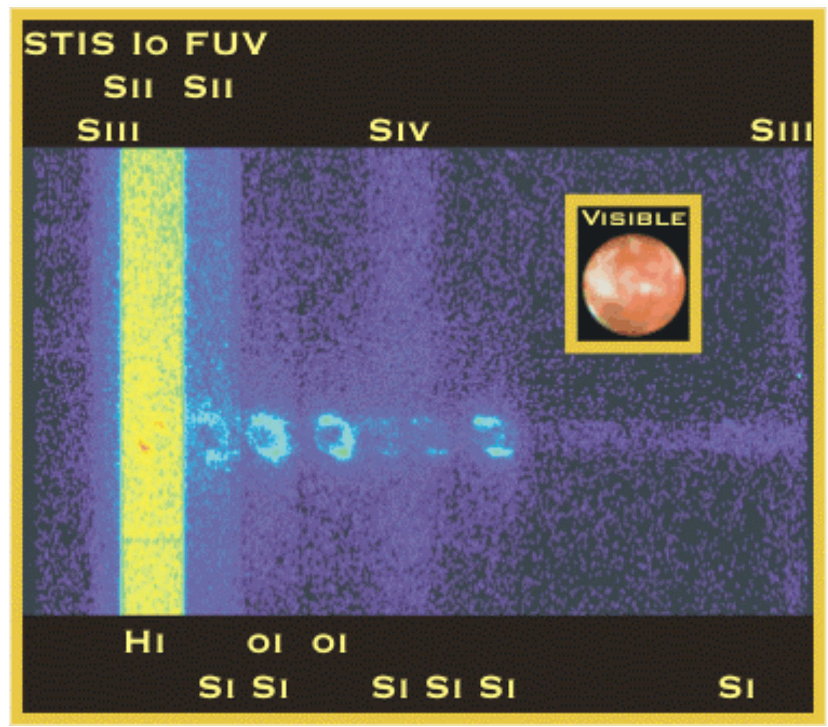
STIS Spectro-imaging

Roesler et al. (1999) provide the first look at the atmosphere of Io in several species at once.

Confirms global nature of coverage, but strongest emission along equatorial regions (could be electron impact)

Full ring shows presence of gas at all latitudes.

Ratios not necessarily consistent with SO_2 sublimation, but images don`t *show* sublimation.

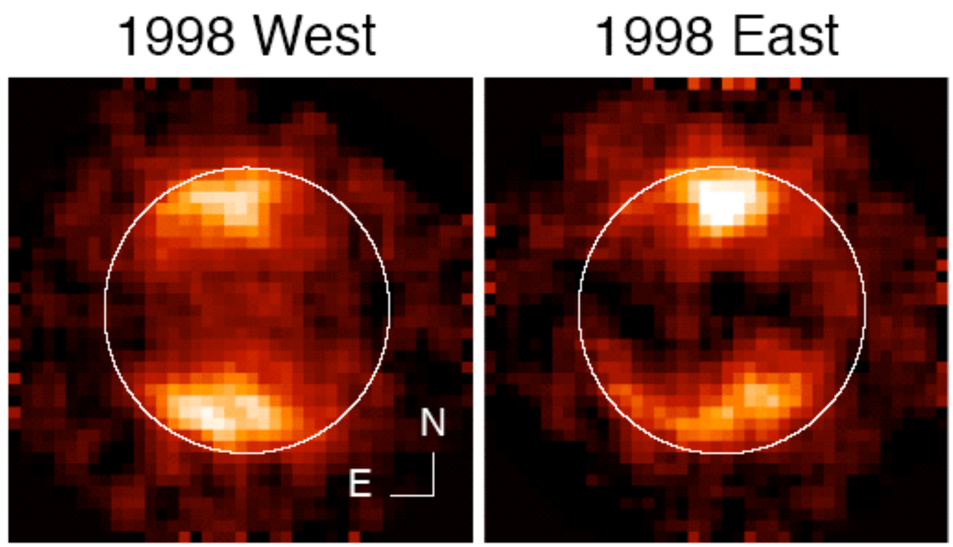


STIS Spectro-imaging

Roesler et al. (1999) also had an interesting discovery regarding H Ly-alpha emission.

The poles were bright!

Early version of paper suggests that this is due to some kind of auroral process, affecting the interpretation of the equatorial data.



Referees catch that it does not have to be emission. It could be reflection

SO_2 is a continuum absorber of Ly-alpha. For the atmosphere to be transparent, the column could be no more than 10^{14} above 50° latitude.

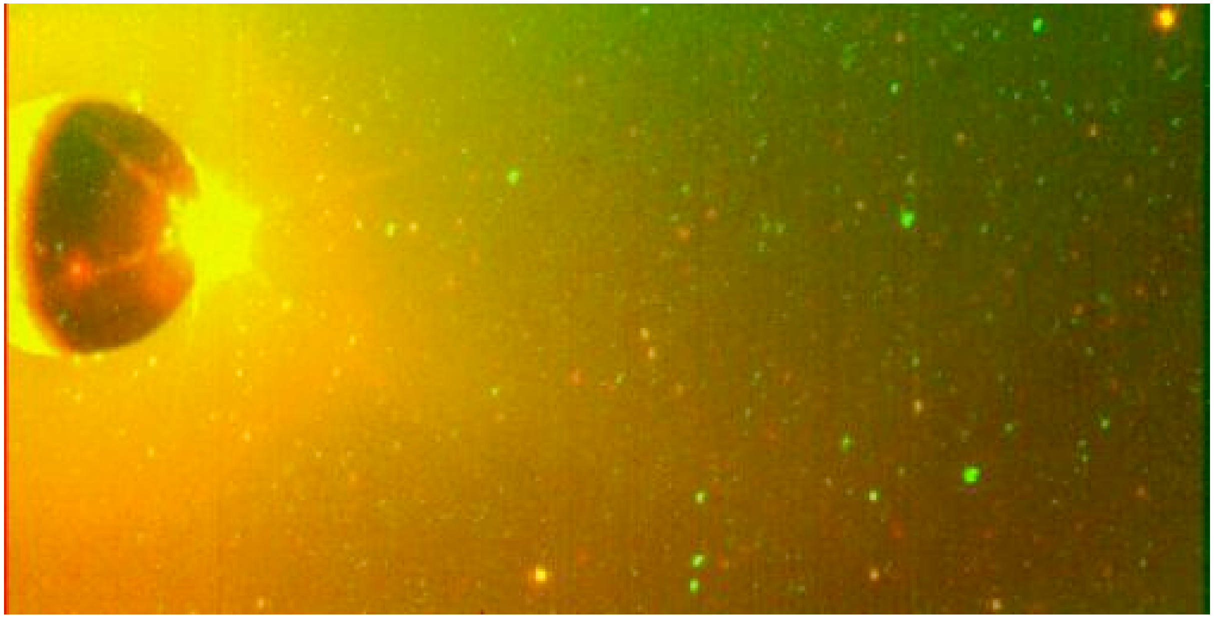
Minor Species:

Since Voyager we have seen spectral signatures of S, O, Na, K, SO, and Cl.

NaCl and KCl are both very low vapor pressure and should be volcanic in origin.

Detection ≠ Density….There are questions about source mechanisms (collision vs. fluorescence)

Metastable emissions (O, SO, and S) give some idea where collision is important.

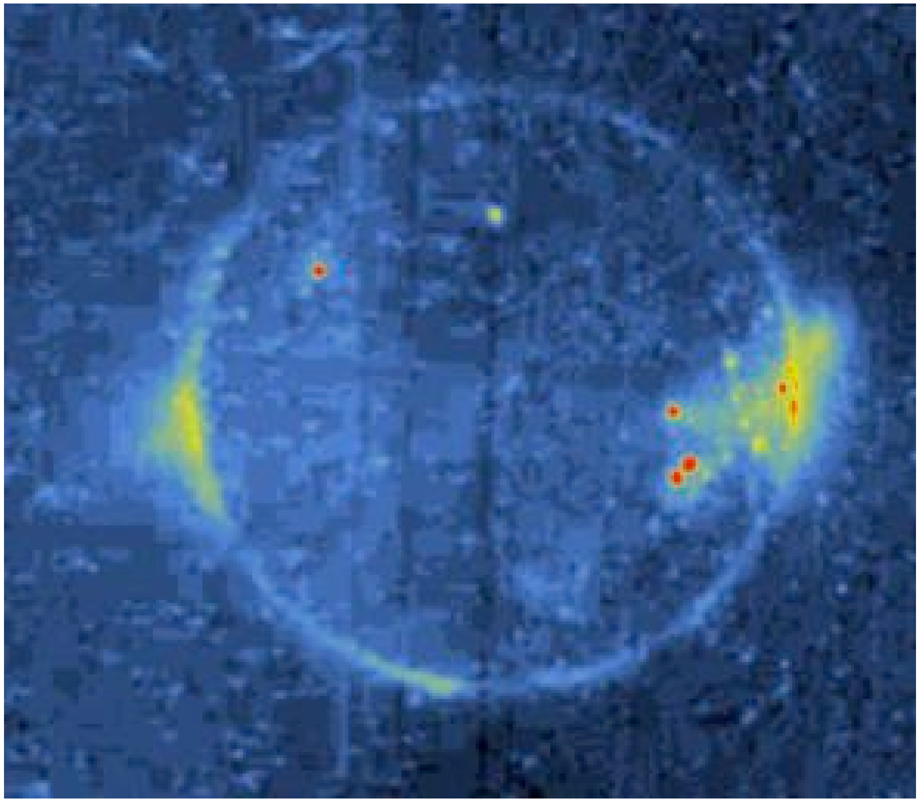


Eclipse:

The nature of a sublimation atmosphere is solvable in eclipse.

Two hours without sunlight cools the surface, allowing a sublimation atmosphere to collapse.

Moreover, only stimulated emissions can be seen in eclipse.



HST (Clarke et al., 2000) show UV emissions from S and O decrease from 1 kR to 100 R over 10s of minutes.

Retherford (2004): Collapse model has SO_2 gone in 5 minutes, atomic species in 30 minutes, but the corona needing 280 minutes. The exosphere is stable longer than an eclipse time.

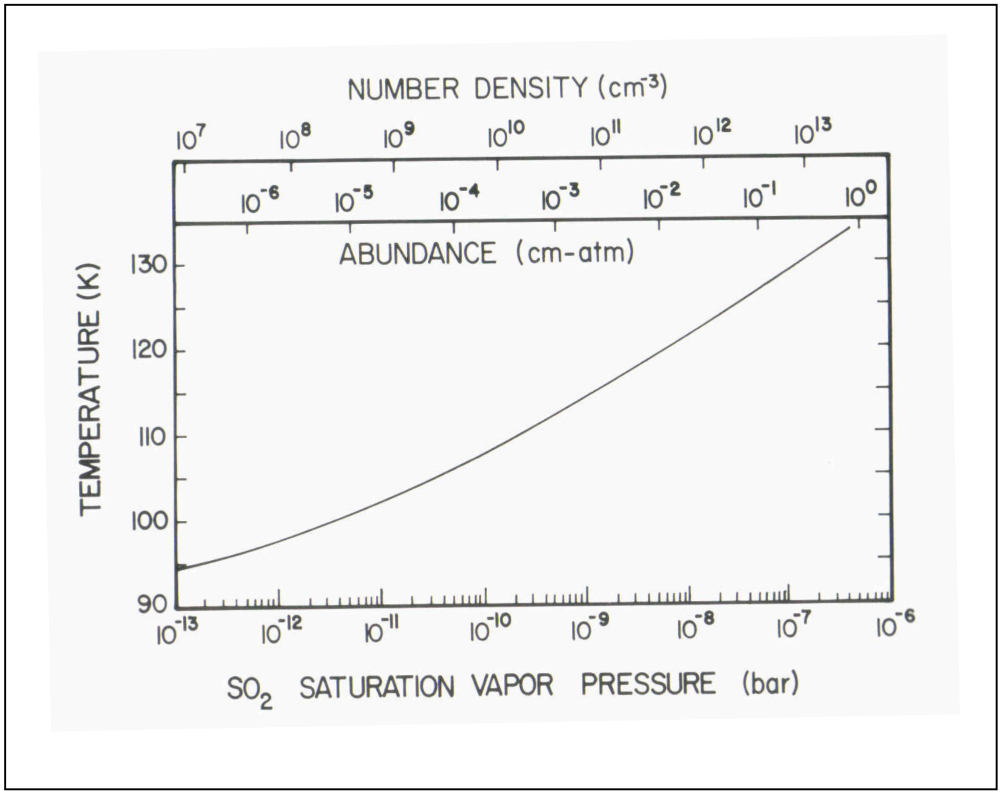
The Atmosphere:

The output of Io`s volcanic activity provides the material necessary to build a thin atmosphere of Sulfur compounds and their photochemical daughters.

The dominant gas species in Io`s atmosphere is SO_2, but this exists in vapor pressure equilibrium at these temperatures.

However it appears that the volcanic regions alone do not provide the observed atmosphere, despite the temperature.

Volcanic regions *do* probably have atmospheric properties that differ wrt the background atmosphere.



Detailed Characteristics:

1) Surface temperatures vary depending on how close one is to the volcanic calderas. This means that there can be peaks in gas liberation from a combination of venting and enhanced sublimation. (Suggests a `patchy` atmosphere)

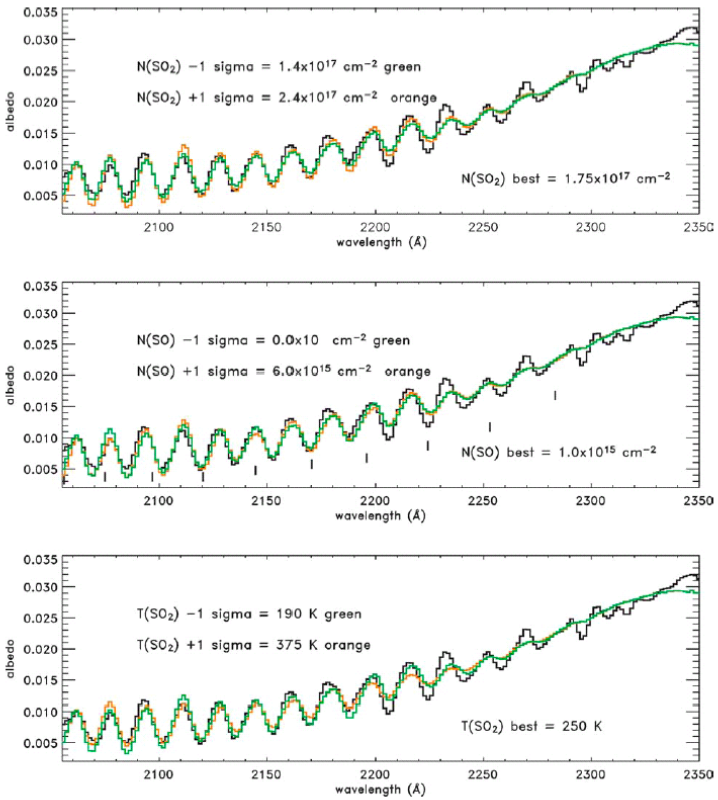
2) Pressure differentials between high T and low T regions will redistribute the atmosphere. The extent of this depends on the ratio of the time constants of wind vs. sublimation equilibrium. (Suggests a more uniform atmosphere)

3) Regions not heated by volcanic activity will experience severe diurnal and eclipse phase variations in atmospheric density. (This is observed)

4) Regions heated by volcanic activity will experience stable conditions with a net outflow of material emanating from the warmest area. (Similar to an active sector on a comet)

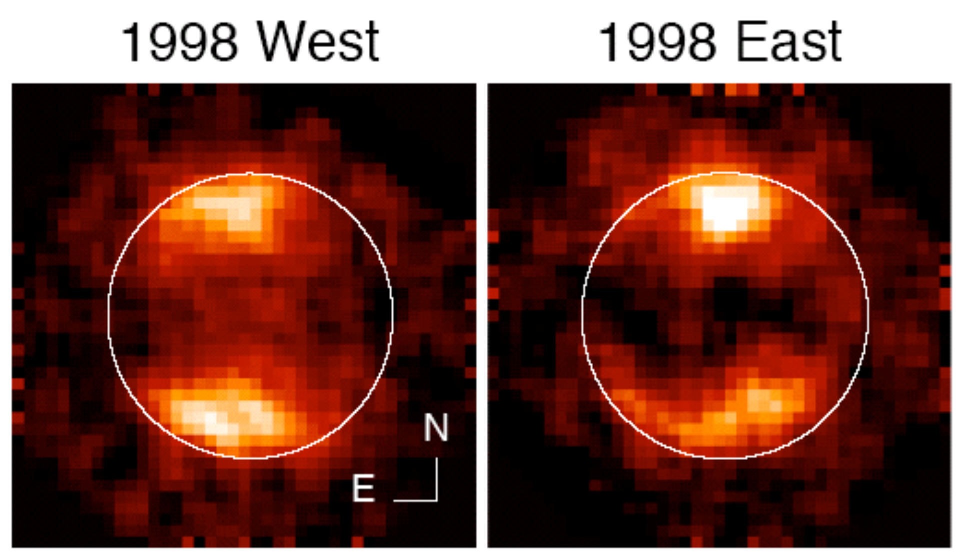
Detailed Characteristics (Part 2):

5) Latitudinal variation in average atmospheric density will occur due to the lower average zenith angle of the Sun (hence lower $T_{surface}$).



Column densities of SO_2 vary from 1.8 x 10^{17} cm^{-2} at the equator to 1 x 10^{16} cm^{-2} at 50° latitude (Jessup et al. 2004).

At high latitudes the SO_2 atmosphere should be very thin. This is observed in Ly-alpha reflectivity (Feldman et al., 2002).

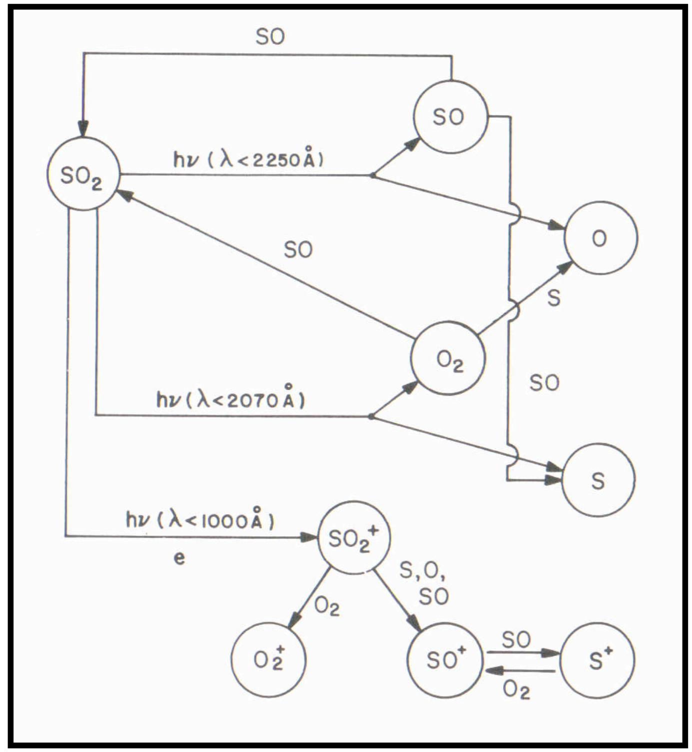


Some constituents may not freeze out and could become dominant at high/low latitudes. (This suggests a patchy composition as well)

Mitigating Factors (Part 3):

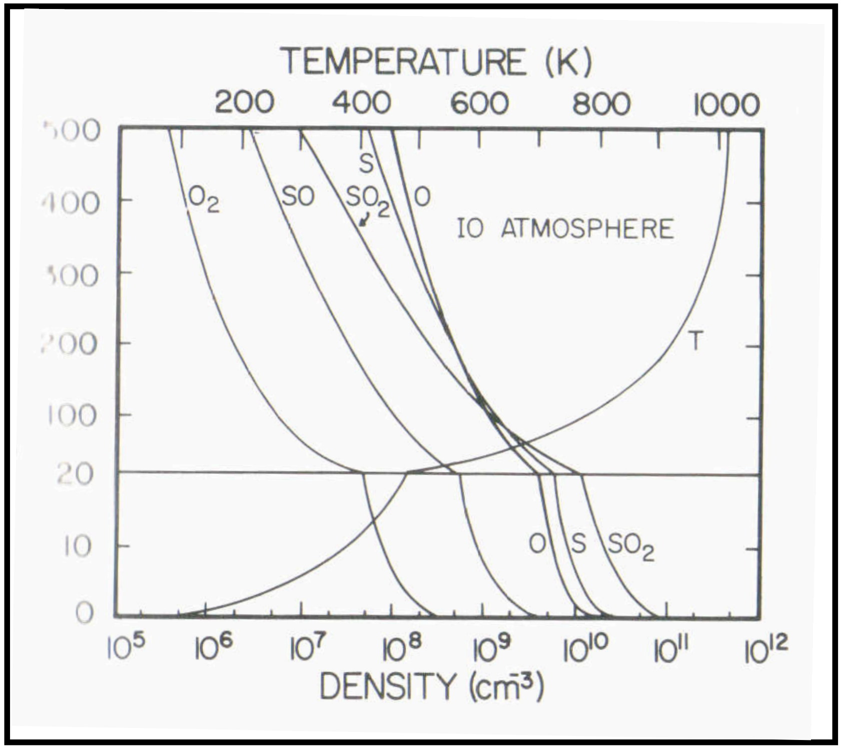
6) **Atmospheric constituents will reach photochemical as well as sublimation equilibrium.**

$SO_2 + h\nu \rightarrow SO + O$	5.6×10^{-6}
$SO_2 + h\nu \rightarrow S + O_2$	2.9×10^{-6}
$SO + h\nu \rightarrow S + O$	6.0×10^{-6}
$O_2 + h\nu \rightarrow O + O$	9.5×10^{-8}
$SO_2 + h\nu \rightarrow SO_2^+ + e^-$	4.8×10^{-8}
$S + h\nu \rightarrow S^+ + e^-$	5.8×10^{-8}
$O + h\nu \rightarrow O^+ + e^-$	1.1×10^{-8}
$SO + h\nu \rightarrow SO^+ + e^-$	2.3×10^{-8}
$O_2 + h\nu \rightarrow O_2^+ + e^-$	2.3×10^{-8}
$SO_2 + O + M \rightarrow SO_3 + M$	$3.4 \times 10^{-32} \exp(-1120/T)$
$SO + O + M \rightarrow SO_2 + M$	3.0×10^{-33}
$S + S + M \rightarrow S_2 + M$	2.0×10^{-33}
$O_2 + O + M \rightarrow O_3 + M$	$1.4 \times 10^{-33} (T/300)^{-2.5}$
$O + O + M \rightarrow O_2 + M$	$3 \times 10^{-33} (T/300)^{-2.9}$
$S + O_2 \rightarrow SO + O$	$2.0 \times 10^{-11} \exp(-2820/T)$
$SO + SO \rightarrow S + SO_2$	$5.8 \times 10^{-12} \exp(-1760/T)$
$O_2 + SO \rightarrow SO_2 + O$	$7.5 \times 10^{-13} \exp(-3250/T)$
$SO_2^+ + e^- \rightarrow SO + O$	1×10^{-7}



A Model Io Atmosphere:

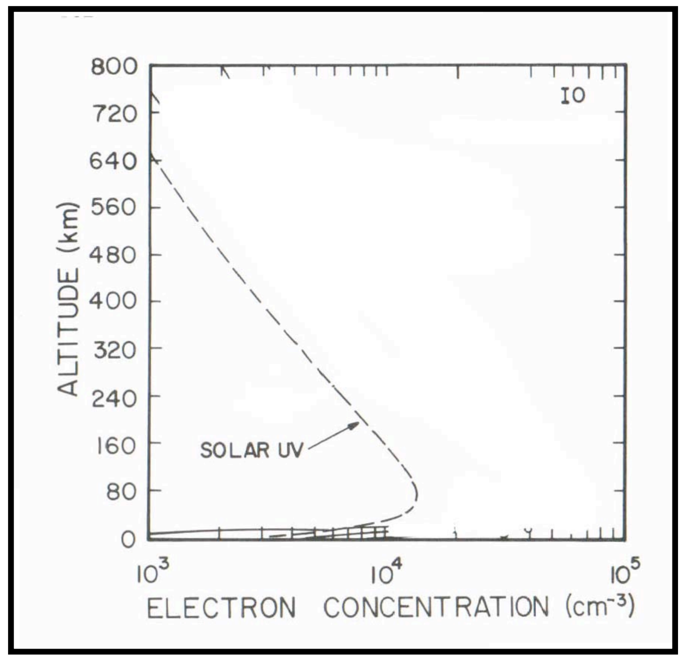
From volcanic activity and solar radiation we can construct an atmosphere for Io.



Below ~20 km the atmosphere is Eddy mixed and in chemical equilibrium.

Above 20 km the atmosphere is defined by molecular diffusion.

We also get an ionosphere for Io.



Using the formula for kinetic T.

$$v_{Thermal} = \sqrt{\frac{2kT}{m}}$$

We find that S and O (and Na) escape Io.

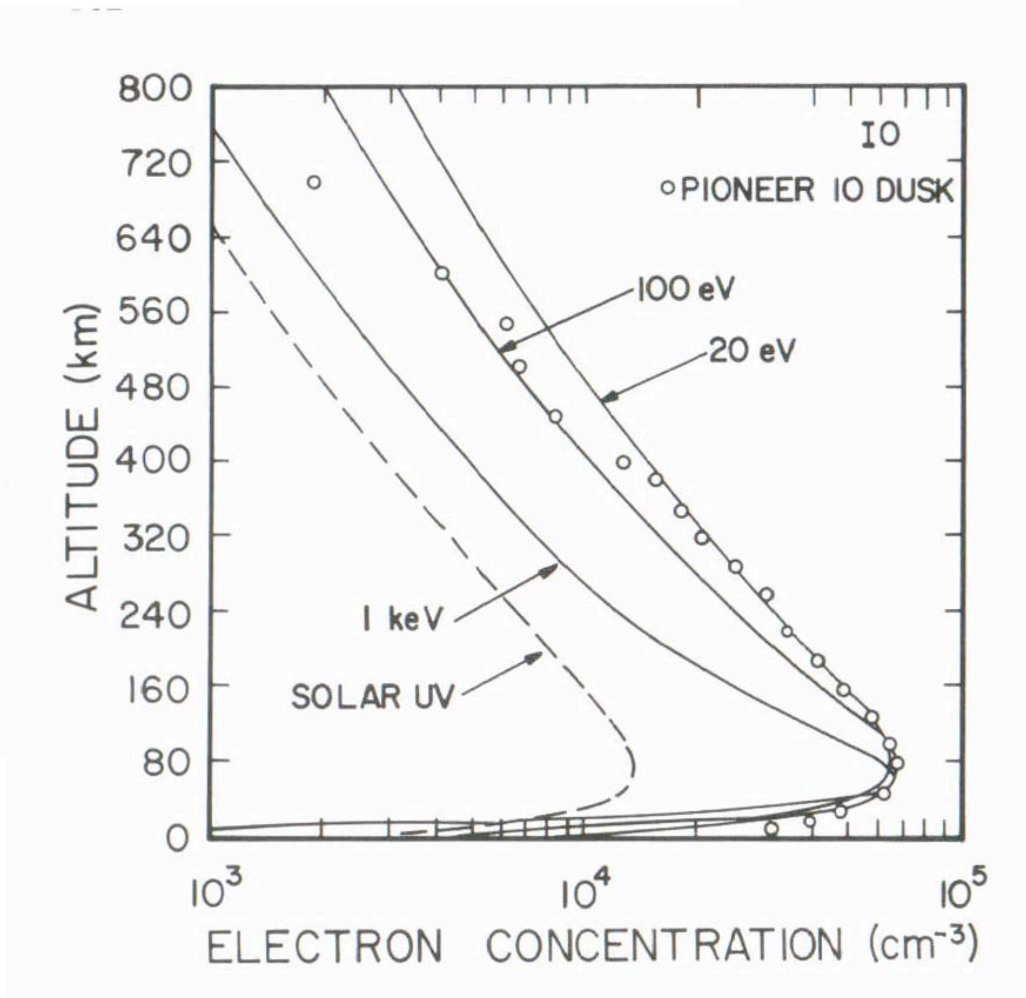
There`s a problem:

Pioneer 10 made measurements of Io`s atmosphere and didn`t quite get what our model suggests.

Pioneer seems to find that Io is being bombarded with ions from the fairly cool to very hot.

Solar Radiation appears to be playing an insignificant role in Io`s atmosphere.

We`ve missed something....



The Bigger Story:

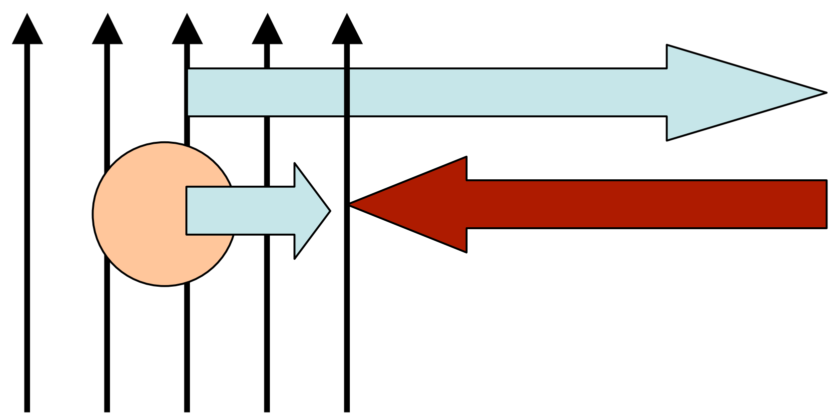
There are three things we`ve ignored up to now.

1) Io has no magnetic field (that we can detect).

2) Io is located deep within Jupiter`s very powerful field.

3) Jupiter`s field rotates with the planet every ***10.5 hours***.

4) In Io`s frame, it is moving its ionosphere through a magnetic field.



We now know enough to figure out what is going to happen as a result of this.

Effects of Magnetic Rotation on Io:

Jupiter`s magnetic field is moving past Io at 54 km/sec. This introduces an electric field.

$$E = V_{Diff} \text{ x } B_{Jupiter}$$

Io`s charged ionosphere then must experience a Lorentz force directed radially away from Jupiter.

$$F = \frac{qE}{c}$$

Thus, the ions begin to move, but the neutrals (q=0) do not. The result is a crush where ions move through collisionally the neutrals.

We treat the collisions like conductivity in a resistor, such that from Ohm`s law

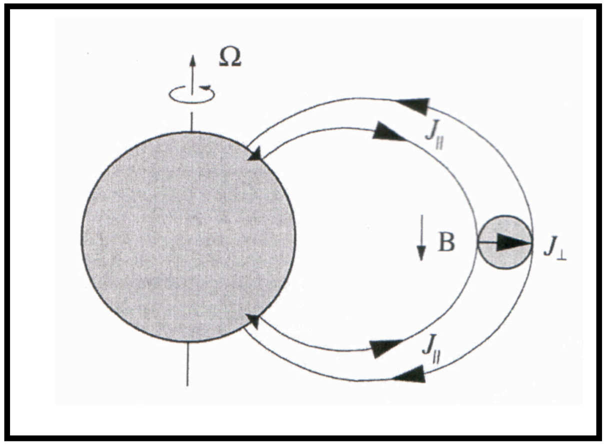
$$j = (\sigma)E \qquad \text{and} \qquad Q_{Joule} = (\sigma)E^2$$

Thus Io should be like a battery embedded in Jupiter`s magnetic field.

Consequences:

There are two detectable ways of seeing this interaction.

1) If Io is a battery, then Jupiter`s magnetic field and resistive ionosphere should form a circuit.



Do we see evidence for this?

Yes!

More Consequences:

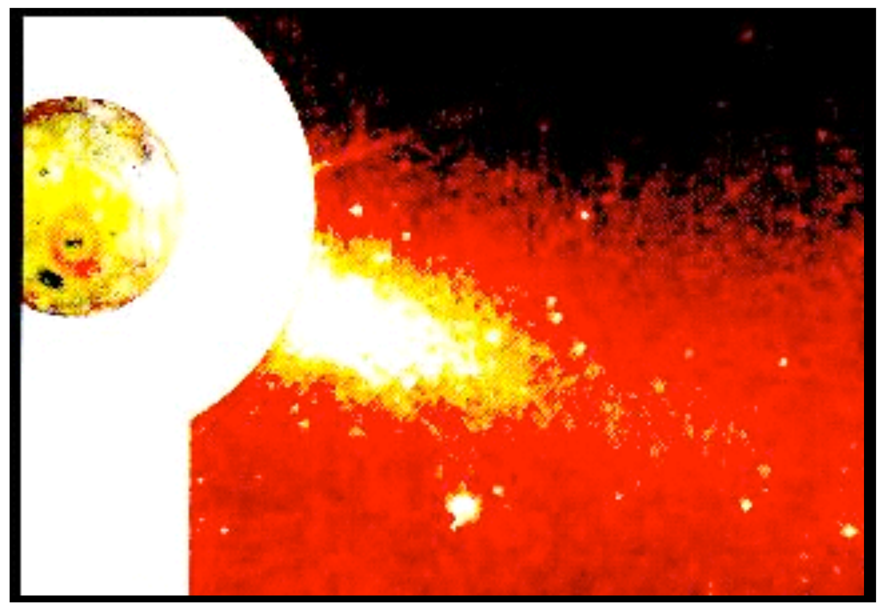
2) Another consequence of the relative motion of the field is from the crossing of ion and neutral flows.

Ions will be accelerated radially away from Jupiter, but are held by the magnetic field.

But what if charge exchange occurs? $(A^+ + B \Rightarrow B^+ + A^*)$

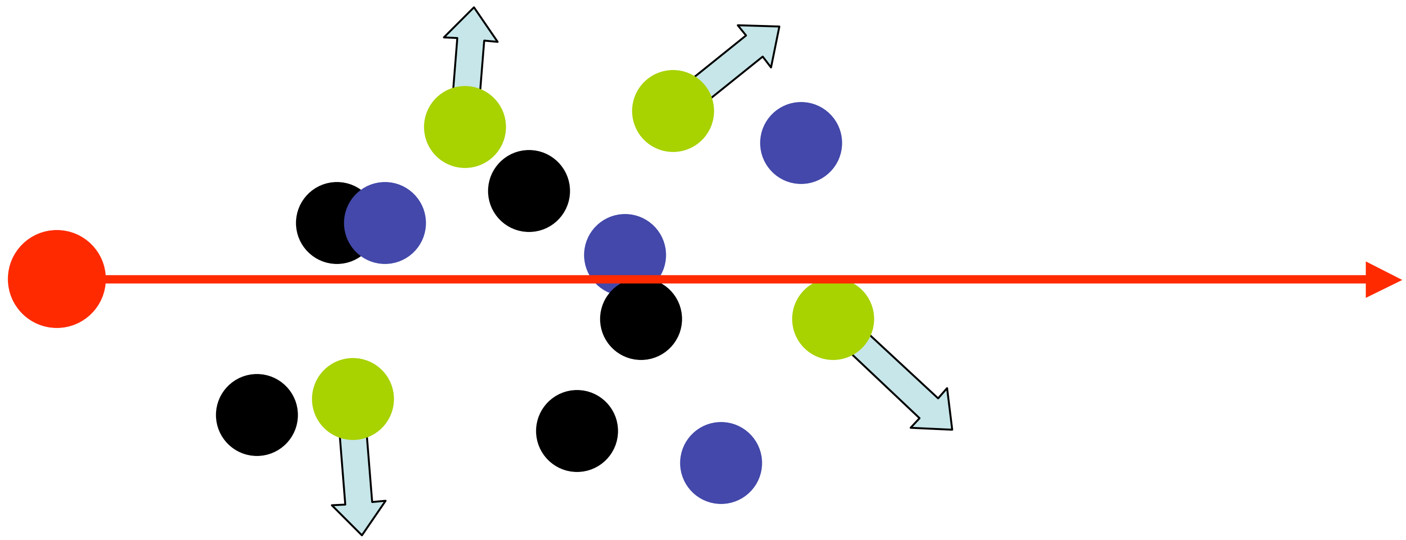
If the exchange takes place high in the atmosphere, the fast neutrals will `jet` away from Io in the radial direction from Jupiter.

This jet is observed....



Stripping the Atmosphere:

A final consequence comes from the effect of torus plasma on the atmosphere.

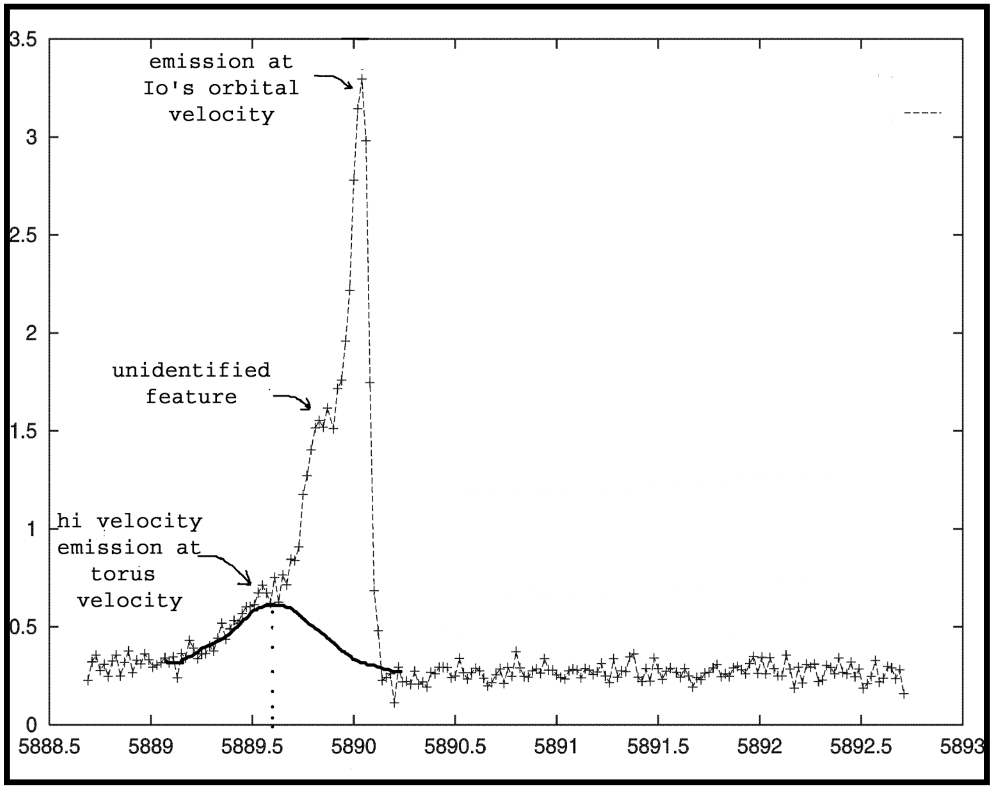


1) Collisions with ions penetrating the atmosphere will Joule heat the neutrals, impact ionize others, and knock some out of the atmosphere altogether. The heating and ionization will expand the atmosphere and increase the ion density.

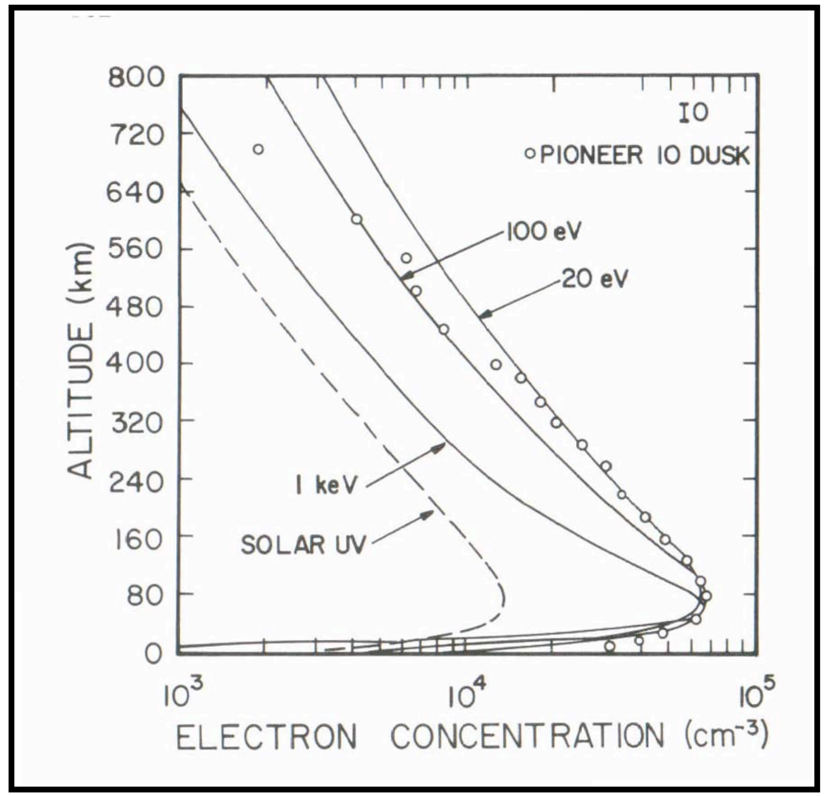
2) Charge exchange with neutrals will create fast particles that have more than the escape velocity for *both* Jupiter and Io. This process can eventually strip away an atmosphere that isn`t continually sourced from volcanic activity.

Evidence of the Atmospheric Interaction:

Evidence for stripping can be seen in emission lines from Io`s atmosphere.

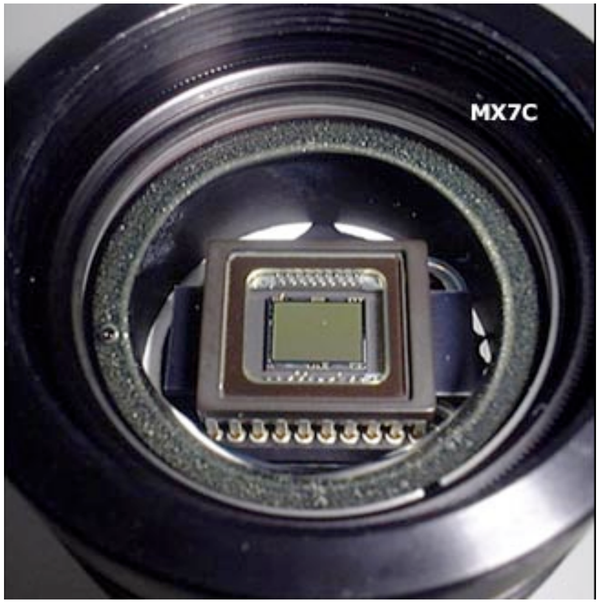


Pioneer 10 already showed us how much the torus interaction controls conditions in Io`s ionosphere.



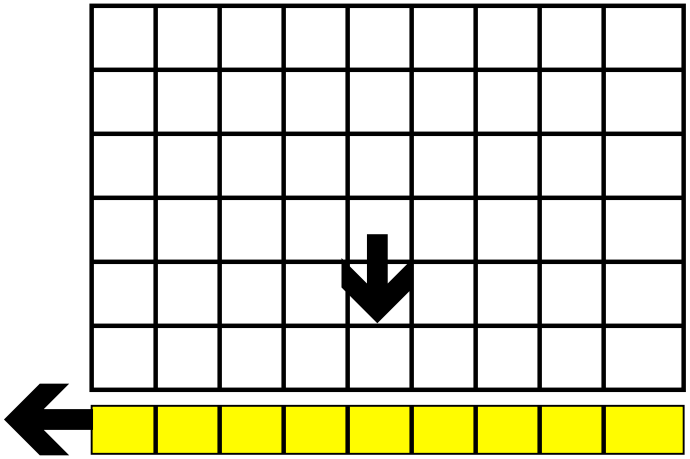
Basic Processing of Raw Data:

All of the exposures we have obtained were read onto a charged coupled device (CCD) of *some* sort.



CCD imagers are essentially arrays of light buckets.

Data is read out in a variety of ways, but the basic technique is to use a controlled voltage to ‘push’ the photons in a ‘shift register’ that is then read out pixel by pixel to a data frame.



Three major issues with CCDs have historically been.

1) Charge transfer efficiency

2) Read noise

3) Dark noise

CCD Noise Sources:

Noise in a CCD takes 5 forms.

- Read Noise: The accuracy of the pixel by pixel readout.
  - RN the same in every pixel of every FRAME
  - RN is lower for longer read times, ranging from 1-10e
- Dark Noise: Random photon events generated in the CCD.
  - DN is a strong function of temperature
  - DN is linear with exposure time
- Gain: A set conversion of photons-charge
  - Gain is a way to alter the dynamic range of a CCD
  - Gain reduces the fidelity of low signals.
- Bias: A flat voltage applied to the signal to prevent negative voltages. It exists only as an extra signal, but without noise.
- Cosmic Rays and Bad Pixels/Columns:

Optical and Environmental Concerns:

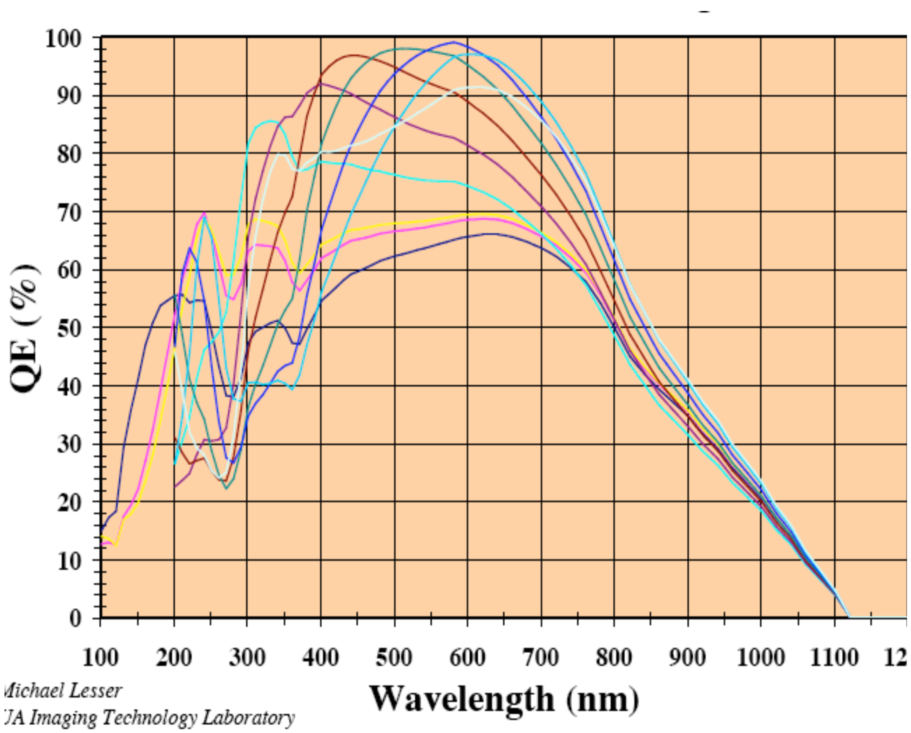
There are several issues that affect the performance of the optical system and total sensitivity to consider:

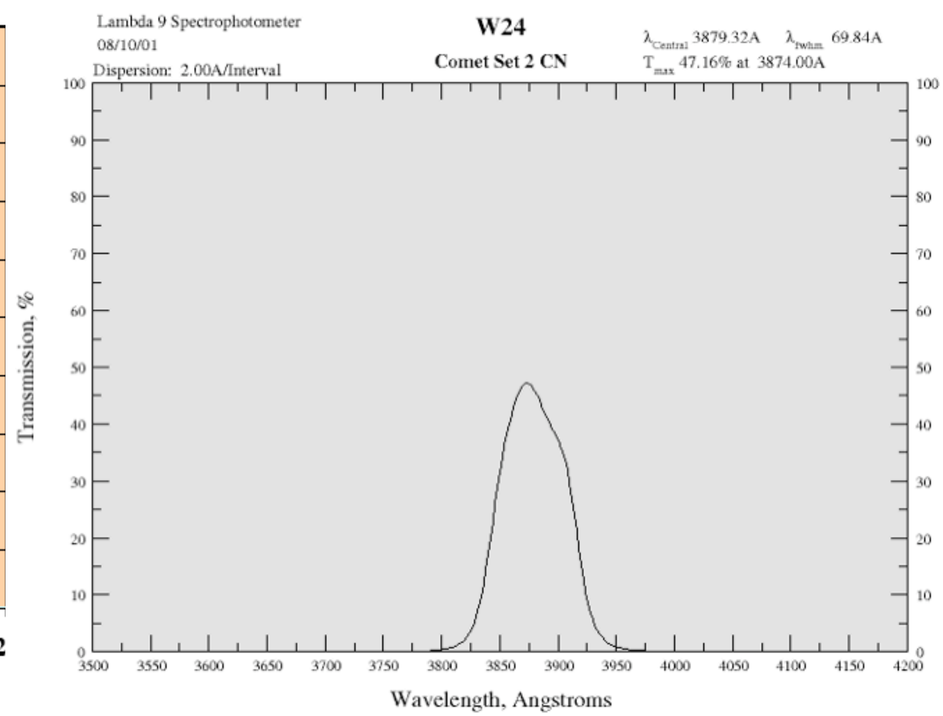
- Focus/seeing: The quality of the imaging.
  - Seeing is the scintillation of the atmosphere (twinkle)
  - Focus is the image quality of the telescope.
    - Focus changes with location depends on seeing.
- Guiding: The ability of the telescope to track the target.
  - Very important for moving targets like Jupiter/Io/Torus
  - Not all telescopes can handle this.
- Rotation: The sky rotates about any fixed point along with the Earth.
  - Most telescopes automatically correct for this.
  - Some fixed focal plane instruments do not.

Optical and Environmental Concerns:

There are several issues that affect the performance of the optical system and total sensitivity to consider:

- **Wavelength Sensitivity:**
  - **Defined by optics and CCD performance.**
  - **Filters are used to isolate specific spectral regions.**
  - **Sensitivity changes with location in the field of view.**

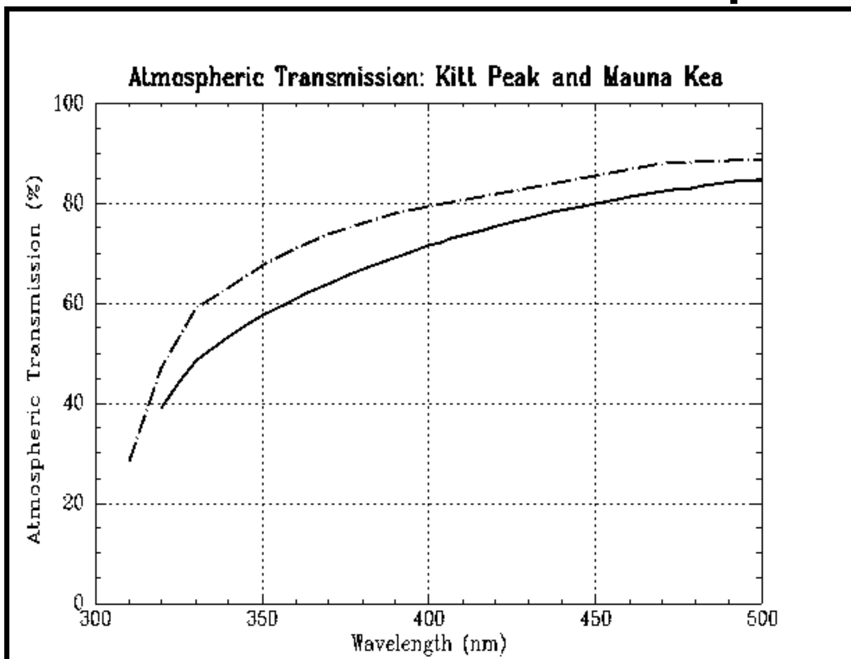




Optical and Environmental Concerns:

There are several issues that affect the performance of the optical system and total sensitivity to consider:

- **Airmass and Clouds:**
  - **Airmass is a measure of the column of air through which you observe.**
  - **Clouds are a pain!!!**



Airmass attenuation can be calculated using a simple equation:

$$Airmass = \sec(X) - dx$$

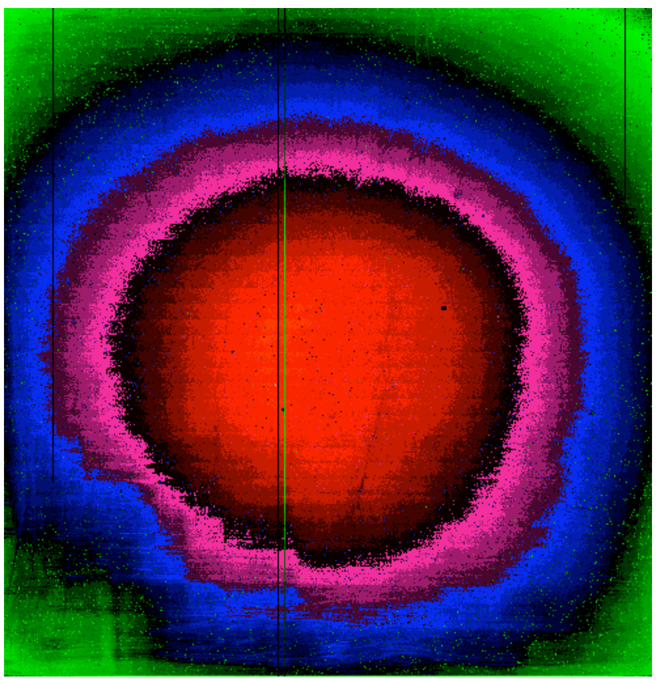
where

$$\sec(X) = \left(\sin(D)\sin(R)\right)^{-1} + \left(\cos(D)\cos(R)\cos(HA)\right)$$

Basic Reduction:

Before working on data we need to process the images to account for the effects:

- **Airmass: Use either the basic equation/table OR standard star.**
- **Field Sensitivity: Take images of a uniform (flat) source.**
- **Bias: Take zero exposure length images.**
- **Bad Pixels: Identify in flat/bias.**



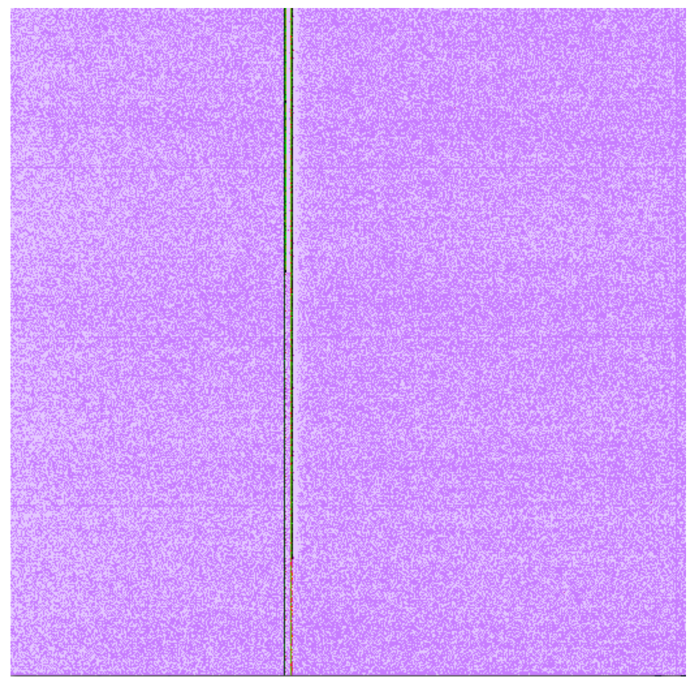


Image Reduction:

From processed images we can separate the continuum (solar blackbody) from the torus (SII) emission.

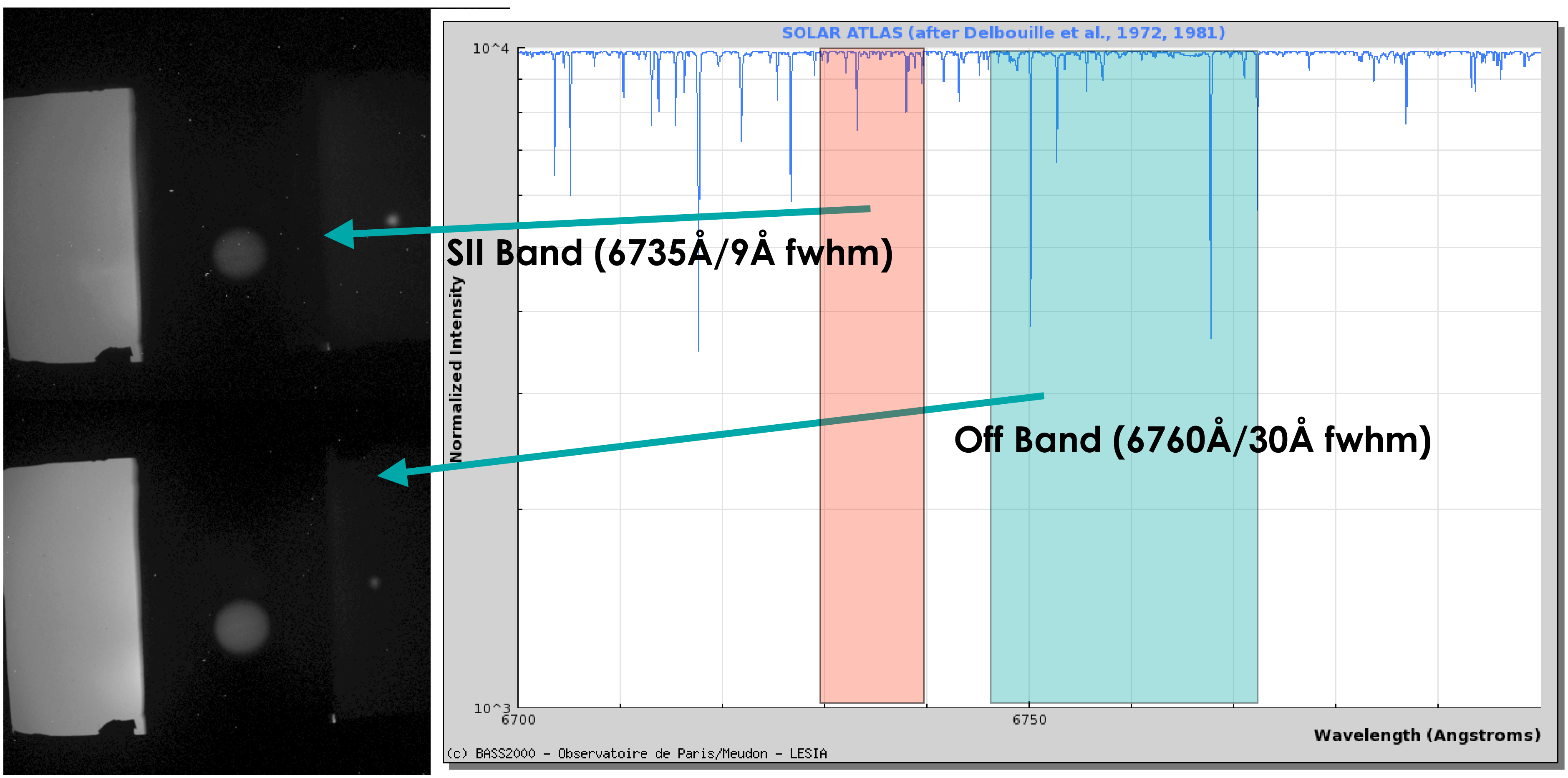


Image Reduction:

If you correct all of the defects in the images and do the processing correctly, then you will be rewarded with nice pictures of the Torus!