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Lyman-α Imaging of the SO_2 Distribution on Io

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Abstract. Imaging spectroscopy of Io in the ultraviolet (1160 – 1720 Å) was carried out with the Space Telescope Imaging Spectrograph on HST on three dates in October 1997 and August 1998. Among the initial results was the observation of concentrated regions of H I Lyman-α flux near the poles of Io that exhibited a morphology and temporal variability different from those of the atomic oxygen and sulfur emission regions seen near the equatorial limbs. We examine the suggestion that the primary source of Lyman-α emission is surface reflected solar radiation that penetrates the thin polar atmosphere, but is strongly absorbed by the thicker SO_2 atmosphere near Io's equator. Spectral and spatial analyses lead to derived SO_2 column densities that are in good agreement with those derived from earlier HST observations of Io's albedo in the 2000 – 2300 Å wavelength range. The Lyman-α images clearly illustrate features of Io's atmosphere that have been deduced from previous observations and theoretical modeling: a non-uniformity with respect to the sub-solar point dominated by a freezing out of the SO_2 near the poles and variation with both longitude and time due to the variability of the sources of the atmospheric gas. Lyman-α imaging is demonstrated to be an extremely powerful and direct way to globally map the dynamic atmosphere of Io.

Introduction

The nature of Io's tenuous SO_2 atmosphere has been of great interest since its discovery by *Pearl et al.* [1979] because of its dynamic and volatile sources. There have been several subsequent detections of SO_2 gas on Io, by *Lellouch et al.* [1992], *Ballester et al.* [1994], *Trafton et al.* [1996], and *McGrath et al.* [2000]. In several additional observations the presence of SO_2 gas has been inferred indirectly [*Sartoretti et al.*, 1996; *Spencer et al.*, 1997; *Hendrix et al.*, 1999]. Although some of the earlier observations have pointed to global scale spatial inhomogeneities in the atmosphere, possibly associated with major volcanic sources, most have been spatially unresolved disk averages from which the actual distribution of gas over the surface could only be estimated. The disk-averaged observations have been fitted nearly equally well by a large range of models with the extremes being either areal coverage of a small fraction of the surface by a relatively large SO_2 column ($\geq 10^{17}$ cm^{-2}), or areal coverage of 100% of the surface by a relatively small column ($\leq 10^{16}$ cm^{-2}). The only direct, spatially-resolved measurements [*McGrath et al.*, 2000] strongly favor the larger fractional coverage, smaller column abundance scenario, and a picture of the Io atmosphere in which SO_2 gas is ubiquitous, with only modest lateral inhomogeneities.

The addition of the Space Telescope Imaging Spectrograph (STIS) to the Hubble Space Telescope in February 1997 provided an opportunity to perform ultraviolet imaging spectroscopy of Io and its surroundings. Observations of Io were made in 1997 and 1998 with the low resolution G140L grating, which covers the 1150–1720 Å spectral range. A preliminary analysis of the spatially resolved spectra from 1997, focusing on the S I and O I bright spots near Io's equatorial limbs, was recently presented by *Roesler et al.* [1999]. Enhanced H I Lyman-α emission is seen near the poles but appears to be uncorrelated with the atomic oxygen and sulfur emissions. *Roesler et al.* discussed two scenarios: that this emission may indicate the presence of an Iogenic source of atomic hydrogen, or that it is reflected solar radiation attenuated by an SO_2 atmosphere concentrated largely near Io's equator. In this paper we examine the latter suggestion in detail, and find it to be the more plausible explanation. The required SO_2 column density and areal coverage is most consistent with the smaller column abundance, larger fractional coverage regime cited above.

Observations

Spectra were obtained during three contiguous HST orbits on October 14, 1997 and August 23, 1998, and during two orbits on August 27, 1998. The observation parameters are listed in Table 1. Details of the STIS mode used for the observations can be found in *Roesler et al.* [1999]. Two separate time-tagged spectral images are obtained in each orbit. Usually, one of these exhibits a high geocoronal Lyman-α background (10–15 kR as opposed to 2.5–4 kR during the dark part of an HST orbit) as well as strong O I λ1304 airglow emission due to the illumination of the Earth's upper atmosphere by sunlight. These are excluded in the composite images and analyses presented below.

Individual spectra (two per orbit) were extracted by summing the data over 71 pixels (1.″73) along the slit centered on Io (note that one pixel is 0.″0244 × 0.″0244 and that the dispersion is 0.584 Å pixel^{-1}). The background, particularly the geocoronal Lyman-α, was obtained by summing 151 pix-

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Table 1. Observation and Composite Image Parameters.

Date	Sub-Earth Longitude (°)	Io Diameter	Phase Angle (°)	Exposure Time (s)	Sub-Earth Optical Depth[a]	Sub-Earth Column Density[a] (cm^{-2})
1997 Oct 14	243–272	1″.09	10.6	3280	2.3	3.0×10^{16}
1998 Aug 23	295–325	1″.24	5.0	3650	1.1	1.4×10^{16}
1998 Aug 27	36–53	1″.24	4.2	3325	3.5	4.5×10^{16}

[a] Upper limit due to over-subtraction of interplanetary Lyman-α.

els (3″.68) along the slit on both sides of Io, and averaging the two. The results with the background subtracted are shown in Figure 1 for two cases, one from 1997, the other from 1998. The extracted spectrum has been rebinned by four pixels to enhance the signal/noise ratio. The unusual shape of the strong spectral lines of O I and S I results from the spatial location of these emissions at Io's limb.

Longward of 1520 Å the signal is principally reflected solar radiation. To model this component, solar spectra taken with the SOLSTICE instrument on UARS *Woods et al.* [1996] appropriate to the solar activity level on the date of observation (determined by the solar 10.7 cm radio flux) were convolved with an assumed uniform reflecting disk of Io's radius. These are overplotted in Fig. 1. From this fit, the geometric albedo can be derived from the ratio of the reflected flux, $F_{Io}(\lambda)$, to the solar flux at 1 AU, $F_{\odot}(\lambda)$:

$$p(\lambda) = \frac{F_{Io}(\lambda)\pi d^2}{F_{\odot}(\lambda)\Omega_{Io}}\phi(\theta,\lambda)$$

where d is the Sun-Jupiter distance in AU, Ω_{Io} is the solid angle of Io as seen from Earth, and $\phi(\theta,\lambda)$ is the phase function at phase angle θ. With the assumption of unity for $\phi(\theta,\lambda)$, the derived albedo between 1520 to 1700 Å is 1.9% for the 1998 (both east and west) observations and 1.5% for the 1997 observations. This could be the result of a phase angle dependence (see Table 1), or be due to variations in surface composition with longitude. There are no reported observations of Io's albedo at these short ultraviolet wavelengths. At 2325 Å *Sartoretti et al.* [1996] found little difference in albedo for phase angles between 7° and 10° and only a slight variation (from 2.2% to 2.5%) with longitude.

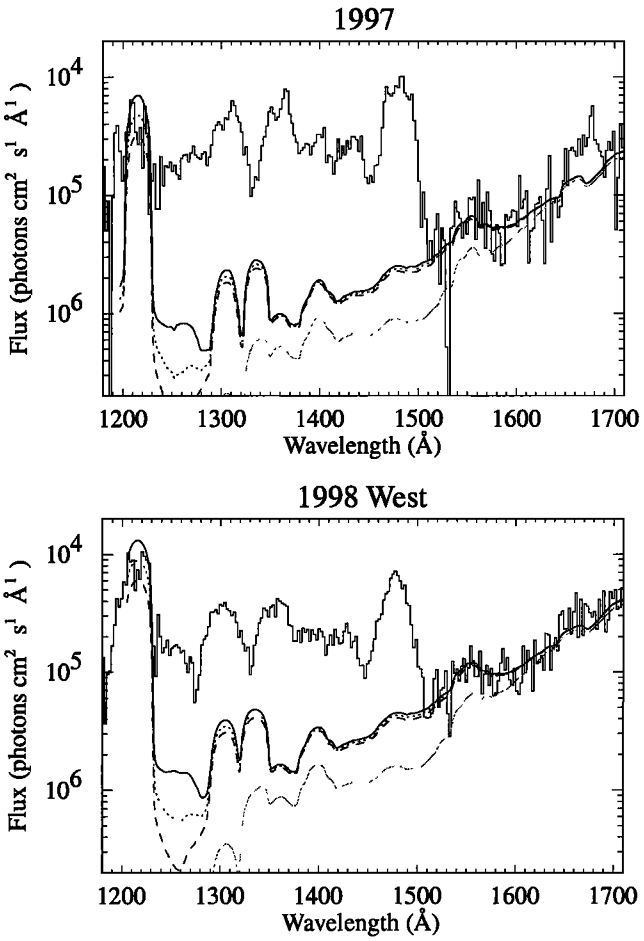

Figure 1. Spectra of Io from 1997 (top) and 1998 (bottom). A solar spectrum, convolved with a disk of Io's diameter, unattenuated and passing both ways through a column of SO_2 are overplotted. The curves correspond to column densities of 0 (solid), 0.5 (dotted), 1.0 (dashed) and 10 (gray) $\times 10^{16}$ cm^{-2}, respectively. The spectra shortward of 1520 Å are predominantly emissions of O I and S I [*Roesler et al.*, 1999]. Note the presence of S I emission at 1667 Å.

Making the further assumption that the albedo at 1216 Å is the same as that between 1520 to 1700 Å, both sets of data, but particularly the 1997 data, predict higher values of H I Lyman-α than is observed, as seen in Fig. 1. The likely source of the attenuation is absorption by SO_2 in Io's atmosphere since the absorption cross-section at Lyman-α is 3.9×10^{-17} cm^2, considerably higher than the band cross-section longward of 2000 Å [*Manatt and Lane*, 1993] that has been used in prior analyses. The utility of this approach results from the fact that the ~ 1 Å wide solar Lyman-α line acts as a nearly monochromatic source of radiation at wavelengths where SO_2 is a continuum absorber.

To examine the plausibility of this suggestion, the solar flux was modeled with attenuation by a uniform plane-parallel atmosphere of fixed SO_2 column density (two way absorption). These models are also shown in Fig. 1 and give a good fit to the Lyman-α flux with a global SO_2 column density ranging from $5 - 10 \times 10^{15}$ cm^{-2}, in excellent agreement with the global column densities derived by *Ballester et al.* [1994], *Trafton et al.* [1996], and the spatially resolved column densities of *McGrath et al.* [2000]. Note that this column density of SO_2 produces negligible effects on the derived albedo between 1520 and 1700 Å. However, an SO_2 column density of ~ 10^{17} cm^{-2} would produce a significant distortion in the region longward of 1520 Å that is not seen in the reflected solar spectrum of Fig. 1. The structure seen in the Lyman-α line, indicative of spatial variations in the optical depth of the absorber, requires a detailed analysis of the Lyman-α images themselves.

Lyman-α images were constructed using the flat-fielded counts ("flt") files from the HST pipeline processing rather

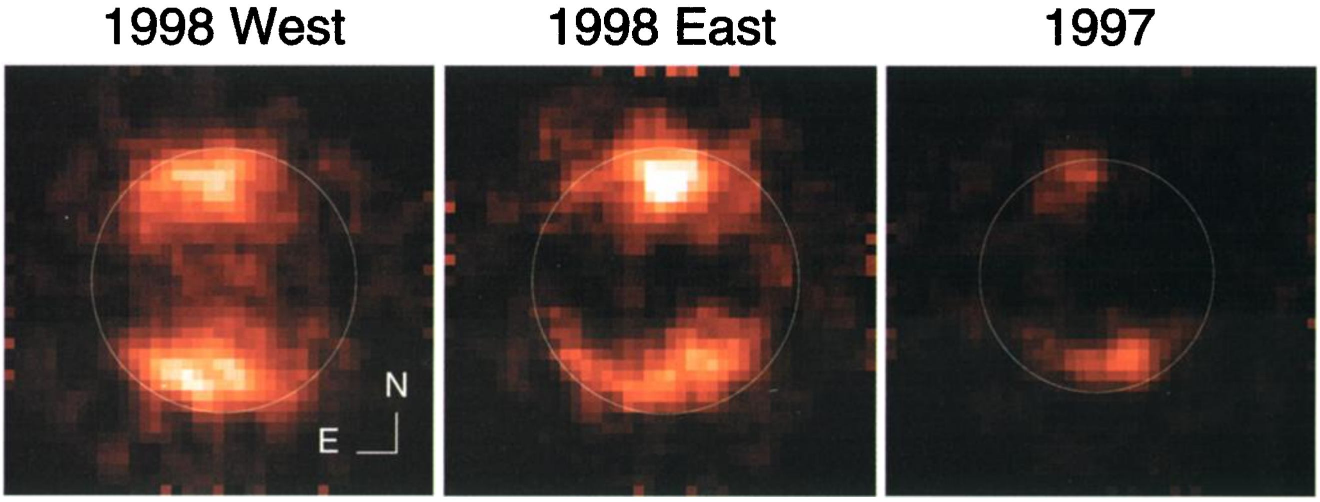

Figure 2. Extracted Lyman-α images of Io. Details of the exposures are given in Table 1.

than the fluxed two-dimensional image ("x2d") files used to generate Fig. 1. This was done to avoid distortion introduced by the rapidly changing sensitivity across the 2″ wide slit, which spans 1192 to 1239 Å. To obtain sufficient counts in each pixel, for each observation epoch three low background exposures were added together. These were taken over contiguous HST orbits resulting in a smearing of the images over a range of sub-Earth longitudes as given in Table 1. Total integration times are given in Table 1. Geocoronal background was evaluated away from Io along the slit and subtracted from the resulting 82 × 82 pixel array. Each image was then rotated to align Jovian north along the vertical axis, rebinned to 41 × 41 pixels (each pixel now 0.″049 on a side), and smoothed by 3 in both directions. The results are shown in Figure 2, and a contour plot of the 1998 West observation, calibrated in kR, is shown in Figure 3. The images are characterized by bright polar regions and darker equatorial regions, variable with longitude, due to the absorption of Lyman-α radiation by SO_2.

These images clearly illustrate the features of Io's atmosphere that have been deduced from previous observations (in particular, the recent results of *McGrath et al.* [2000]) and theoretical modeling (see the discussion in *Ballester et al.* [1994]), namely a non-uniformity with respect to the sub-solar point dominated by a freezing out of the SO_2 near the poles and variation with both longitude and time due to the variability of the sources of the atmospheric gas. Ideally, these images could be inverted to produce images of SO_2 column density, but the relatively low signal/noise ratio in the images favors a slightly different approach described in the next section. Nevertheless, given the availability of sufficient observing time, we have identified an extremely powerful and direct way to globally map Io's dynamic atmosphere.

In order to extract quantitative information about the abundance of the presumed absorbing gas, SO_2, a spatial profile of the Lyman-α emission is extracted along the polar axis by summing 11 columns (0.″54) centered on the sub-Earth point. Assuming that the poles are reflecting solar Lyman-α as if from a uniform reflecting disk (with reflectivity of 0.05), the application of Beer's Law leads to the determination of optical depth, τ_0, at the sub-Earth point, listed in Table 1 together with the corresponding SO_2 column density, which is found to be in the range of $(1-4) \times 10^{16}$ cm^{-2}. Note that these values of τ_0 (and SO_2 column density) are upper limits, as no account has been taken of the interplanetary Lyman-α glow from beyond the orbit of Jupiter that is blocked by Io and that was included in the background subtraction. To examine this effect, detailed modeling of the distribution of interplanetary H atoms (*e.g., Clarke et al.* [1995]) is required. In lieu of such, a plausible brightness of 300 rayleighs was added to each image array before the extraction of τ_0, and the values in Table 1 were reduced to 1.4, 0.9, and 1.9, respectively. The result is clearly sensitive to the value of the interplanetary background used and warrants further study.

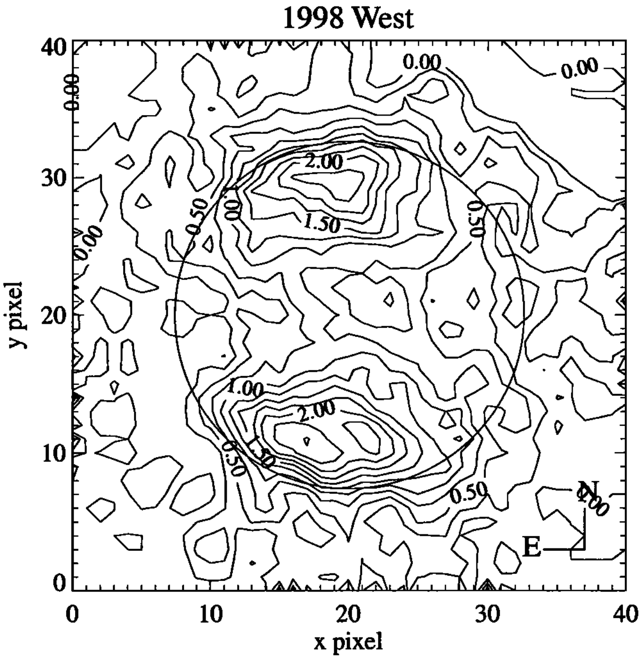

Figure 3. The first panel of Figure 2 shown as a contour plot. The units are kilorayleighs and the pixel size is 0.049 arc-seconds on a side.

Iogenic Hydrogen

To date there is no definitive detection of hydrogen-bearing molecules on Io, although there is evidence for protons in the Io plasma torus and pickup protons in the vicinity of Io [*Frank and Paterson*, 1999]. The two principal excitation sources of Lyman-α involve atomic hydrogen in Io's atmosphere: resonance scattering of solar Lyman-α, and electron impact, both of which should produce limb brightening. The g-factor for the first process is 6.0×10^{-5} photons s^{-1} atom^{-1} and a vertical H column density of $\sim 3 \times 10^{13}$ cm^{-2} at mid latitudes is needed to produce the peak brightness of 2 kR (see Fig. 3), where curve of growth effects have been included. If such were the case, then Io should have a Lyman-α brightness above the limb of $\sim$ 3 kR, which is incompatible with the data of Fig. 3 that would allow at most a few hundred rayleighs in a 200 km resolution element. Electron impact excitation is less efficient than resonance scattering. Upstream of Io, the torus electrons have a density of ~ 3600 cm^{-3} and temperature of ~ 5 eV, which in conjunction with the applicable excitation cross section yields an excitation rate less than 20% of the resonance scattering rate.

Another possible source is charge exchange of a proton with an atom or molecule that converts the proton into an H(2p) atom followed by prompt emission of a Lyman-α photon. In order for the reaction to be resonant and have a large cross section the other atom or molecule would need an ionization potential of $13.6 - 10.2 = 3.4$ eV. No major or minor constituent in Io's atmosphere satisfies this criterion. According to *Frank et al.* [1996] the electrodynamic interaction of the torus plasma with Io's atmosphere slows the torus plasma to velocities of ~ 1 km s^{-1}. At these speeds endothermic charge exchange reactions have very small cross sections. Thus, charge exchange would make a negligible contribution to the observed 2 kR Lyman-α emission.

In conclusion, reflected solar Lyman-α radiation from the surface at mid and high latitudes is the most plausible explanation for the STIS observations. Other sources discussed above could yield only a very minor contribution to the overall 2 kR intensity measured by STIS.

Conclusion

These analyses demonstrate that Lyman-α imaging is a powerful technique to globally map the spatial abundance variation of the presumed dominant gas in Io's atmosphere, SO_2. This is so despite the limitation that the signal/noise ratio in the data is lowest in regions on the disk where the SO_2 column abundance is highest and where small scale variations are likely to be indicative of the presence of surface sources of the gas. Our initial results suggest an SO_2 column density $\sim (1 - 4) \times 10^{16}$ cm^{-2} in the equatorial sub-Earth/sub-solar regions decreasing to less than 10^{15} cm^{-2} in the polar regions, which is in excellent agreement with the column densities of $(0.7 - 3.25) \times 10^{16}$ cm^{-2} in different regions reported by *McGrath et al.* [2000], which suggests that the column abundance decreases with increasing latitude. The hemispherically averaged SO_2 column density is consistent with the equivalent SO_2 abundance inferred by *Ballester et al.* [1994] and *Trafton et al.* [1996], but in serious disagreement with the order of magnitude or more higher values reported by *Lellouch et al.* [1992], *Sartoretti et al.* [1996] and *Hendrix et al.* [1999]. Long-term variability of the SO_2 column density is clearly evident in a comparison of the 1997 and 1998 data and the 1998 data show a marked longitudinal asymmetry as well.

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