Synergetic observations of Io’s atmosphere in 2010 from HST–COS in the mid-ultraviolet and IRTF–TEXES in the mid-infrared

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A B S T R A C T

We report on mid-UV spectroscopy of Io’s SO2 atmosphere from the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST), and compare to contemporaneous ground-based mid-infrared spectroscopy of the atmosphere. Our motivation is to evaluate the consistency of atmospheric parameters derived by different observational techniques, and in particular to verify the atmospheric densities and longitudinal distribution derived from the disk-integrated mid-IR observations, which depend on assumptions about the atmospheric temperature and distribution. Six disk-integrated COS observations, evenly spaced over all Io longitudes, were taken in October of 2010. Spectra were obtained using the G225M grating, with wavelengths ranging from 2100 Å to 2340 Å. At these wavelengths, the SO2 absorption signature of Io’s atmosphere is seen in reflected sunlight. The spectra were fitted using a latitude-dependent atmospheric spatial distribution constrained by earlier disk-resolved observations, with SO2 column density, temperature, and SO abundance as variables. Equatorial SO2 column densities of between 0.26 and 1.28 \( \times 10^{17} \) cm\(^{-2} \) were derived, depending on Io’s central longitude. We compare these results with disk-averaged 19 \( \mu \)m mid-IR spectroscopy in thermal emission from the NASA Infrared Telescope Facility, taken at multiple central longitudes only four months prior to the mid-UV observations. The derived SO2 column abundances from the ultraviolet and mid-IR observations agree to within the uncertainties at comparable longitudes, confirming our earlier mid-IR derived abundances. In addition, both show the large longitudinal variations of atmospheric density seen previously in the mid-IR and Lyman-\( \alpha \) observations, but never before mapped systematically in the mid-UV. Best-fit UV-derived atmospheric temperatures, constrained by UV band shape, were up to 200 K, higher than the <150 K temperatures derived from the IR data, though even the best-fit temperatures did not fit the UV band shapes well. Models in which the atmosphere was assumed to be in vapor pressure equilibrium with low thermal inertia SO2 frost, with column abundance thus depending on distance from the sub-solar point, could not fit the UV or IR data without invoking very high sub-solar densities that are inconsistent with other observational constraints. Instead, the apparent latitude-dependent atmospheric distribution suggests support by some combination of low-latitude volcanoes and high thermal inertia frost. An upper limit SO abundance of 2.7% was derived from the COS data.

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1. Introduction

Io’s constant and global volcanism releases internal energy generated by gravitational tidal heating (Peale et al., 1979). The total power output of approximately \( 10^{14} \) W (Peale, 1999; Moore et al., 2007; Veeder et al., 2012) ultimately drives the hundreds of volcanoes that have so far been detected (Lopes et al., 2004). This volcanic activity produces a sulfur dioxide (SO2) dominated atmosphere, with sub-solar column densities in the \( \sim 10^{17} \) cm\(^{-2} \) range (Spencer et al., 2005), and a surface pressure of \( \sim 10^{-2} \) bar (Lellouch et al., 2007). SO2 frost is thought to originate from the condensation of gas released from Io’s SO2 rich volcanic plumes. The volcanic gas not only produces deposits around the volcanoes but is also transported around Io. The frost distribution is a result of the migration and transport of the sublimated frost deposits. During times of Io’s eclipse by Jupiter and at night, the cold surface may allow the atmosphere to condense onto the surface, although we have not seen evidence for frost patches forming at night, despite searches for them (Simonelli et al., 1998). This atmospheric collapse is likely if the atmosphere is in vapor–pressure equilibrium with surface frost, because vapor pressure is strongly dependent on surface temperature (Wagman, 1979). It should be noted however, post-eclipse brightening of O and S atomic lines have been attributed to an atmosphere recovering from collapse (e.g.: Clarke et al., 1994; Wolven et al., 2001).
The relative contributions from frost sublimation and direct volcanic injection to the total density and distribution of the atmosphere are not well known. The study of the atmosphere gives us insight into the physical properties of the frost (as the time-variable frost temperature, inferred from the sublimation atmospheric density, is dependent on frost thermal inertia and albedo), and the global distribution of frost and volcanoes. Atmospheric escape injects a large quantity of molecular and atomic species around Io’s orbit, controlling Io’s neutral cloud and plasma environment, implanting atomic species on the other jovian moons such as Europa. These logenic materials propagate on Jupiter’s magnetic field lines to form the auroral footprints observed at Jupiter’s poles (e.g.: Bonfond et al., 2012). For these reasons and many others, the understanding Io’s atmosphere and its influence in the jovian system is important.

Io’s atmosphere has been observed on numerous occasions with ultraviolet spectroscopy. Ballester et al. (1994) obtained disk-integrated spectra of Io’s trailing hemisphere from 1573 to 2330 Å using the Faint Object Spectrograph (FOS) on the Hubble Space Telescope (HST), determining a hemispheric average SO2 column abundance in the \( \times 10^{16} \) cm\(^{-2} \) range. McGrath et al. (2000), using the same instrument at the same wavelengths as Ballester et al. (1994), made the first disk-resolved observations of Io’s atmosphere, at three locations on the surface. McGrath et al. (2000) found large spatial inhomogeneities in the atmospheric density, between 7 \( \times 10^{15} \) and 3.5 \( \times 10^{16} \) cm\(^{-2} \), a factor of five difference between the densest and least dense locations, indicating a high degree of spatial variation of the atmosphere. The SO2 latitude distribution observed did not follow a simple latitude dependence as expected from an atmosphere under pure vapor pressure equilibrium. This is suggestive that the atmospheric distribution was modified by hydrodynamic flow, in which case the atmosphere would fall off as a function latitude more slowly than the simple vapor pressure equilibrium model (e.g.: Walker et al., 2010). Jessup et al. (2004) obtained HST–STIS (Space Telescope Imaging Spectrograph) disk-resolved spectra of Io’s atmosphere around the anti-jovian hemisphere in the 2000–3000 Å UV range, using a 0.1° wide long slit at a spectral resolution of 6.5 Å. The authors corroborated the findings of Feldman et al. (2000) (discussed below) at Lyman-\( \alpha \) by finding the atmospheric density decreasing from the equator (with a sub-column density of 1.5 \( \times 10^{17} \) cm\(^{-2} \)) towards the poles (2–3 \( \times 10^{16} \) cm\(^{-2} \) near 60°N/S). These mid-UV results show that Io’s atmosphere is spatially inhomogeneous both in latitude and longitude. Latitudinal gradients were also positively identified by ultraviolet imaging. Feldman et al. (2000) showed Io at high latitudes (above 60°N/S) were bright in Lyman-\( \alpha \) light, but much darker at low latitudes. This was attributed to an atmosphere predominantly located at low latitudes that absorbs Lyman-\( \alpha \) light. The poles, having less atmosphere, appeared brighter as Lyman-\( \alpha \) light is reflected back with minimal attenuation. The Lyman-\( \alpha \) brightness at low latitudes was also observed not to increase between the center of the disk and the equatorial limb, leading to the conclusion that the atmosphere does not vary significantly in local time. This is consistent with the idea that the atmosphere is primarily supported by volatiles (Strobel and Wolven, 2001). Feldman et al. (2000) imaged Io in three separate periods in 1997 and 1998 using HST–STIS. The spatially resolved observations were at longitudes on the sub-jovian and trailing hemispheres. The authors derived a sub-column abundance between 1.4 and 4.5 \( \times 10^{16} \) cm\(^{-2} \). Feaga et al. (2009) used HST–STIS imaging observations of Lyman-\( \alpha \) spanning five years to measure the longitudinal variability of the atmospheric SO2 distribution on Io. The maximum average dayside sub-column SO2 column density they detected was \( \times 5 \times 10^{16} \) cm\(^{-2} \) near 140° longitude; the minimum average dayside density of 1.5 \( \times 10^{16} \) cm\(^{-2} \) was observed on Io’s sub-jovian side. Although the absolute values obtained were somewhat lower than Jessup et al. (2004) and Spencer et al. (2005) (discussed below), the overall longitudinal and latitudinal distribution was in agreement, showing growing consensus on the distribution of the atmosphere of Io. Feaga et al. (2009) also attempted to correlate their column densities with heliocentric distance between 1997 and 2001. Because the eccentricity of Jupiter’s orbit increases insolation at Io at perihelion, it leads to increases in the average surface temperature and allows more surface SO2 frost to sublimate near perihelion compared to aphelion, due to the strong temperature dependence of the frost vapor pressure (Spencer et al., 2005). However, no such correlation was found by Feaga et al. (2009). Reliable evidence for the dependency of Io’s atmospheric density with heliocentric distance was not provided until seven years of mid-infrared data were analyzed by Tsang et al. (2012) (see below).

The longitudinal variation of Io’s atmospheric density was first systematically mapped by Spencer et al. (2005) using mid-infrared observations of Io’s disk-integrated thermal emission from the NASA Infrared Telescope Facility (IRTF) with the Texas Echelon Cross Echelle Spectrograph (TEXES) spectrograph (Lacy et al., 2002). The 19 μm non-local thermal equilibrium absorption bands of SO2 were fitted to retrieve equatorial SO2 column densities, assuming a latitude-dependent atmospheric density model, at different sub-observer longitudes. The data, spanning 2001 through 2004, revealed that sub-jovian hemispheric densities (1.5 \( \times 10^{16} \) cm\(^{-2} \)) were less than the anti-jovian hemisphere values (1.5 \( \times 10^{17} \) cm\(^{-2} \)), peaking near 180° longitude, as confirmed by the Feaga et al. (2009) Ly-alpha mapping. The authors also showed the atmospheric kinetic temperature was likely 150 K or lower, as higher temperatures sometimes resulted in emission spectra, which were never evident in the data.

Subsequently, Tsang et al. (2012) showed the atmospheric density as observed at 19 μm from TEXES also shows changes over the course of the jovian year. Between 2001 and 2010, combining new data with older data from Spencer et al. (2005) and Tsang et al. (2012) were able to show the derived equatorial atmospheric density on the anti-jovian side decreased from 1.12 \( \times (0.134) \) \( \times 10^{17} \) cm\(^{-2} \) in 2001 to 0.61 \( \times (0.145) \) \( \times 10^{17} \) cm\(^{-2} \) in 2005, near aphelion. The atmospheric density then rose to 1.51 \( \times (0.215) \) \( \times 10^{17} \) cm\(^{-2} \) in 2010, near perihelion. These densities were retrieved by co-adding spectra from longitudes 90° through 270° for each respective year. These variations are in good agreement with an atmosphere that is in vapor pressure equilibrium with SO2 surface frost whose temperature varies with heliocentric distance, given plausible assumptions for frost albedo and thermal inertia, though a non-varying volcanic component is also required to match the data. The authors were also able to retrieve the atmospheric kinetic temperature, with a mean of \( \sim 110 \) K, and confirmed the persistence of the longitudinal variations of the atmospheric density seen in Spencer et al. (2005).

Because atmospheric parameters derived from different observational techniques depend differently on assumptions about the atmospheric structure and distribution, comparison of near-simultaneous observations at different wavelengths is a valuable check on the reliability of the derived parameters. Therefore, in an attempt to further confirm the spatial distribution of atmospheric SO2 and the derived kinetic temperatures inferred from the mid-infrared data, as well as to try and resolve differences between previously derived atmospheric densities, we have taken disk-integrated spectra of Io at multiple longitudes using the recently installed Cosmic Origins Spectrograph on the HST, and compared them to contemporaneous mid-IR spectra.
2. HST–COS 2100 Å observations

The Cosmic Origins Spectrograph (COS) is a medium resolution ultraviolet spectrograph observing in the 900–3200 Å range with spectral resolving powers between 1500 and 22,000. COS was launched as part of Servicing Mission 4 (SM4) to HST on 11th May 2009 on Space Shuttle Atlantis STS-125. COS began science operations in September 2009. COS is optimized for high sensitivity for point sources and is highly complementary to STIS, in that STIS covers a broader wavelength range and is capable of higher spatial resolution, but is less sensitive than COS. The Primary Science Aperture (PSA) is 2.5 arcsec field stop which passes the aberrated beam from the HST primary mirror – COS thus cannot provide useful spatial resolution across Io’s disk. COS has two channels, the Far Ultraviolet (FUV) channel, covering wavelengths between 900 and 1775 Å, and the Near Ultraviolet (NUV) channel that covers the 1750–3200 Å region. For a more detailed discussion of instrument capabilities, calibration and data reduction, refer to Dixon et al. (2010), Osterman et al. (2011) and Green et al. (2012).

We observed Io with COS between 27th September and 8th October 2010. Details of these observations are given in Table 1. The observations were evenly spaced in lo central longitude to cover the expected lateral variability of the atmosphere as seen in the mid-infrared. All observations were made using the G225M grating, which has a spectral range between 2100 Å and 2500 Å. For point sources, HST–COS has resolving powers between 20,000 and 24,000 for point sources, but because of the width of the PSF of the COS aperture, the extended angular size of the target object reduces the spectral resolution. Io subtends an angular size of 1° in the sky, and with a detector plate scale in the along-dispersion direction of 0.024˚/pixel, a single wavelength from Io illuminates 42 along-dispersion pixels on the detector. Combined with the dispersion of 33 mÅ/pixel for the G225 M grating, we obtain an effective spectral resolution of 1.38 Å (R ~ 1500) for our Io spectra. The NUV MAMA 1024 x 1024 pixel detector is illuminated by three mirrors covering different spectral ranges, which result in three ‘stripes’, with wavelength gaps in the measured spectrum. The selection of the central wavelength thus defines the spectral range that is measured. All Io observations were obtained with a central wavelength setting of 2217 Å, which resulted in coverage of wavelengths between 2017–2101 Å in stripe A, 2136–2200 Å in stripe B, and 2235–2334 Å in stripe C (gaps being 64 Å wide).

During the two weeks of observations, lo was 1.27–1.26° in angular diameter and was at a heliocentric distance of 4.96 AU. Each observation comprises an acquisition sequence followed by the science observation separated into three different exposures. Each exposure is 450 s in length, giving a total exposure of 1350 s per observation. All observations were made in TIME-TAG mode, which records the time and location of each detected photon.

3. HST–COS: data reduction

The data are reduced using the standard Space Telescope Science Data Analysis System (STDS) CALCOS routines, which include flat fielding, dark subtractions and flux calibrations. Wavelength calibration is accomplished by the use of Pt–Ne lamps, which illuminate the detector through the Wavelength Calibration Aperture (WCA). The calibration spectrum is then used to assign wavelengths to the science spectra. A final collapsed and calibrated spectrum is provided by the pipeline for each observation, called an xld, as well as a coadded spectrum for the entire observation where multiple exposures exists, such as in our case, called an xldsum. We therefore have 6 xldsum files, one for each day of observations, which are used as our science data.

The measured lo spectrum (Fig. 1, top panel) is a combination of the incident solar flux, Ioian atmospheric absorption and the surface reflectance. To obtain a spectrum of Io’s atmospheric absorption and albedo only, we divide the measured spectra by a solar flux spectrum. We obtained a solar spectrum, taken on 8th October 2010, as measured by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instrument on the Solar Radiation and Climate Experiment (SORCE) mission (Fig. 1, middle panel). SOLSTICE is a four channel instrument measuring the UV flux from the Sun on a daily basis from 1150 to 3100 Å, at a resolution of 1 Å and sampled every 0.33 Å (McClintock et al., 2005a, 2005b). The measured solar spectrum was a mean from all observations taken within that day. All Io spectra were divided by the same solar spectrum. The radiometric error of the SORCE-SOLSTICE spectrum is ~2% (McClintock et al., 2005a).

To compensate for the different spectral resolutions and line spread functions of the two instruments, we rebin both the SOLSTICE and COS data such that the final spectra both have a spectral resolution of 2 Å (Fig. 1, lower panel). This also helped to increase the signal-to-noise ratio. We also noted that the post-pipeline COS xldsum and xld spectra had a wavelength mis-registration when compared to SOLSTICE data at the same resolution, as determined by matching Fraunhofer lines. The magnitude of the wavelength shift ranged between 0.9 and 1.2 Å, much larger than expected Doppler shifts (<0.3 Å), and the shift only occurred in the first

Table 1
Details of observations made in 2010 in order of observation date and the equatorial retrieved SO2 column densities, assuming the modified latitude model, no SO, and an isothermal, longitude invariant atmospheric temperature of 100 K. All HST–COS observations used the G225M grating, centered at 2217 Å with exposures of 1350 s.

<table>
<thead>
<tr>
<th>19 µm IRTF–TEXES observations</th>
<th>Date and start time (UT)</th>
<th>Io central longitude (°)</th>
<th>IR retrieved equatorial SO2 column abundance (1017 cm–2)</th>
<th>Sub-solar longitude (°)</th>
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<td>2010-05-31 15:10</td>
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<td>0.46 ± 0.14</td>
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<tr>
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<td>0.23 ± 0.15</td>
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<td>1.71 ± 0.13</td>
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<td>1.48 ± 0.13</td>
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</table>

<table>
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<th>2217 Å HST–COS observation</th>
<th>Date and start time (UT)</th>
<th>Io central longitude (°)</th>
<th>UV retrieved equatorial SO2 column abundance (1017 cm–2)</th>
<th>Sub-solar longitude (°)</th>
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</thead>
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<td>0.54 ± 0.08</td>
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<tr>
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<tr>
<td>lbgp02010</td>
<td>2010-10-08 15:22</td>
<td>088</td>
<td>0.91 ± 0.14</td>
<td>085</td>
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two strips (A and B). We corrected for this offset by using a cross-correlation method to minimize the $v^2$ value of the difference between the observed Io COS spectrum and that of the solar SOLSTICE spectrum. This method is described in detail in Tsang et al. (2012) where a similar spectral mis-registration problem occurred with the IRTF–TEXES 19 lm data. Each strip is independently cross-correlated to give a constant shift within that strip. The shift is determined before binning to 2 Å resolution. Once COS wavelengths are matched to the SOLSTICE spectrum, the COS spectra are divided by the solar spectrum, which yields spectra that contain only Io’s surface albedo and absorption by its atmosphere (Fig. 2). The Io spectra are converted from their native radiometric units of ergs/s/cm$^2$/Å into units of geometric albedo. This is done according to the equations in Feldman et al. (2000) and Feaga et al. (2009) by rationing Io’s flux to the solar flux, accounting for Io’s distance from the Sun at the time of the observations, the solid angle that Io subtends at Earth and Io’s phase angle during observations. We assume zero phase angle, discussed further in Section 7, as our observations are near $/C24$ phase. The calibration pipeline also provides estimates on the radiometric errors. The statistical errors provided combine Poisson statistical noise, given the magnitude of the measured fluxes, with the propagated errors from both the flat field and the dead time corrections. These radiometric errors are also converted to albedos by dividing by the solar spectrum and converted to albedo according to Feldman et al. (2000) and Feaga et al. (2009).

4. Io atmospheric model in the UV

We use a model described by Jessup et al. (2004, 2007) for calculation of the two-way transmission spectra from Io’s atmosphere. We briefly summarize the details of their model. The SO$_2$ transmission, $T_{SO2}$, is calculated using the Malkmus band model as described previously by Jessup et al. (2004), Zhu (1994) and Ballester et al. (1994). In its simplest form $T_{SO2} = \exp \left(-\pi y(\lambda)/2 \times [(1 + 4\sigma(\lambda, T)/\pi y N) - 1]^{1/2}\right)$, where $\sigma(\lambda)$ is the wavelength, $\lambda$, and temperature, $T$, dependent SO$_2$ absorption cross-section, $N$ is the SO$_2$ column density, and $y$ is a parameter that assesses the saturation effects of the gas absorption in the wings of the bands as a function of wavelength. For our purposes, the transmission is calculated as a function $N/\mu$, where $\mu$ is the cosine of the solar zenith angle.
As done previously, the $\gamma$-factor is derived by a least squares fit between the exact $k$-distribution of the SO$_2$ absorption cross-section and the Malkmus model. In the early 1990s, the value of the $\gamma$-factor in the 2100–2300 Å region was determined from the Freeman et al. (1984) data taken at 20 mÅ spectral resolution (Ballester et al., 1994). For the present analysis, following the work of Jessup et al. (2004), we more precisely determined the value of the $\gamma$-factor in the 2100–2300 Å region by utilizing the higher 5 mÅ spectral resolution SO$_2$ cross-section measurements obtained by Stark et al. (1999) at 295 K. Additionally, improvements to the characterization of the temperature dependence of the SO$_2$ gas absorption cross-section have been achieved by utilizing the recent laboratory measurements of the SO$_2$ gas cross-section data taken at multiple temperatures (160 K, 198 K, and 295 K), by the same instrument and with near identical spectral sampling and resolution (Rufus et al., 2009, 2003; Blackie et al., 2011; Stark et al., 1999). Following the work of Jessup et al. (2004), the temperature dependence was derived assuming the usual function form, i.e. the wavelength dependent absorption cross-section, 

$$ (\sigma(\lambda)) = (\sigma(\lambda))_0 k^{-\gamma} \exp(-B(\lambda)/T) $$

where $\sigma_0$ and $B$ are constants and $T$ is raised to an exponential power of $n = 1.5$ in order to account for the fact that the SO$_2$ molecule is non-linear.

We attempt to replicate the absorption signatures recorded in the UV spectra by calculating a grid of $58 \times 17$ SO$_2$ transmission matrix utilizing 58 SO$_2$ column densities ranging from $1 \times 10^{15}$ cm$^{-2}$ to $4 \times 10^{16}$ cm$^{-2}$, with grid increments between $1 \times 10^{15}$ cm$^{-2}$ and $2.5 \times 10^{16}$ cm$^{-2}$ at 17 different SO$_2$ gas temperatures, ranging from 100 K to 500 K, at 25 K increments. To assess the impact of SO gas absorption on the observed disk-integrated UV spectra we also calculated SO transmission spectra with 59 SO column densities ranging from 0 to $4 \times 10^{16}$ cm$^{-2}$ at various grid resolutions. The SO transmission spectra are calculated at a single gas temperature of 300 K, as the cross-sections have only been measured at this temperature (Phillips, 1981). Examples of atmospheric transmission as a function of modeled parameters are shown in Fig. 3.

Fig. 3A shows that with increasing gas density the SO$_2$ gas band depth increases, and structure emerges in the wings of the bands. Fig. 3B shows that with increasing temperature the absorption in the wings of the bands becomes more important and impacts the continuum level between the absorption bands. Fig. 3C shows that because the SO laboratory data was taken at low resolution we know only the broad details of the gas absorption signature in the wings (and in fact the peak absorption is probably also under predicted).

These spectra are combined with an assumed atmospheric distribution model to create disk-averaged spectra to be compared with observations, accounting for airmass variations across the disk. We use bi-linear interpolation to determine spectra at parameters intermediate between the pre-calculated values. The two main atmospheric distributions we consider are the modified latitudinal model (MLM) and the solar incidence angle model (SIAM), both plotted Fig. 4. The MLM (Fig. 4 left), also used by Spencer et al. (2005) and Tsang et al. (2012), is a modification to a latitudinal profile in which the atmosphere is in vapor pressure equilibrium with the surface frost of uniform albedo and diurnally-constant temperature. Therefore, in this model the atmosphere has no local time dependence (constant with longitude), and only depends on latitude, due to the decreasing frost temperature with decreasing insolation at higher latitudes. We then modified this profile to better fit the observations by Jessup et al. (2004), by assuming the equatorial column abundance follows vapor pressure equilibrium from the equator to 32$^\circ$ latitude, where the abundance is then held constant until 50$^\circ$ latitude. The abundance then returns to the sublimation model from 50$^\circ$ to the poles. The other a priori atmospheric model we use is the SIAM (Fig. 4 right), where the atmosphere is assumed to be in vapor pressure equilibrium with frost whose temperature varies with solar incidence angle assuming instantaneous equilibrium with sunlight, with uniform albedo and zero thermal inertia. The model atmosphere therefore only depends on solar incidence angle (distance from the sub-solar point). In the SIAM, for simplicity we assume zero solar phase angle, i.e. the sub-solar point is in the center of the disk. As the maximum solar phase angle seen from Earth is only 11$^\circ$, this is a reasonable assumption. These two end-members describe two quite different atmospheres. As will be described in Section 7, because the IR and UV observations are most sensitive to changes of the atmospheric density on different parts of Io’s disk, comparing IR and UV data to the MLM and the SIAM allows us to investigate the distribution of Io’s atmosphere. For more information on these and other atmospheric models, see Spencer et al. (2005). Most of the results we present use the modified latitude model. We also assume that the atmospheric kinetic temperature is uniform with altitude as well as with location on the disk.

The best-fit values of equatorial column density and temperature were determined by using a retrieval model that interpolates between calculated grid points and minimizes the reduced $\chi^2$ value between the observations and synthetic spectra. A Monte Carlo model was used to estimate the errors on the retrieved quantities. This is done by taking the best-fit spectra, adding random noise to it at the level of the residual (the difference between the synthetic and the observation) and refitting that spectrum for column abundance and temperature. This is repeated 50 times and the standard deviation is taken as the error in the retrieved values from that observation. These models and techniques are described further in Spencer et al. (2005) and Tsang et al. (2012).

### 5. Mid-infrared 19 μm observations

We also compare the HST–COS observations taken in October 2010 with those from the TEXES instrument on the IRTF obtained four months earlier in June 2010. The TEXES data and reduction procedures are described at length in Tsang et al. (2012) and are summarized here. The observations span between 529.0 cm$^{-1}$ and 530.7 cm$^{-1}$ (18.90–18.84 μm) at a resolution of 57,000. There are six observations, predominantly on the anti-jovian and trailing hemispheres (Fig. 5). The observations were ratioed against Callisto to remove telluric and instrumental features. The Callisto spectra at these wavelengths are featureless and were taken before and after obtaining lo spectra to bracket airmass. The observed multiple $v_3$ vibrational bands of SO$_2$ were fitted using the same MLM and SIAM model atmospheric distributions used to fit the COS UV spectra (Fig. 4). Line strengths were determined using non-local thermodynamic equilibrium calculations of vibrational temperature as a function of altitude, assuming constant kinetic temperature with altitude (Spencer et al., 2005). The model was fitted to the observations with the AMOeba code, and the equatorial column densities and temperature of SO$_2$ were retrieved. AMOeba is described in Tsang et al. (2012). Fig. 5 also shows the best-fit spectra from the model (red) to the observations (gray), including the residuals (green).

Unlike in the UV, at 19 μm the atmosphere is illuminated from below by thermal emission from the solar-heated passive surface and the volcanic hot spots, so a model of passive and volcanic surface temperatures is also incorporated into the disk-averaging model (Spencer et al., 2005). Retrieved atmospheric densities are biased towards the atmosphere above the warmest regions on the surface, near the sub-solar point and above the volcanoes. According to our adopted model, disk-averaged emission from volcanic hot spots and the passive surface are comparable at 19 μm (Spencer et al., 2005). The reflected-light 2100 Å HST–COS atmo-
spheric signature however is weighted entirely by surface albedo and is thus not biased in the same way (and is insensitive to the atmosphere over the hot spots, which occupy only a small fraction of the surface area). If our assumed atmospheric spatial distribution is correct, similar (meaning to within errors) retrieved abundances are expected from both the observed UV and IR spectra, while differences in retrieved abundances would point the way to model improvements on the spatial distribution of the atmosphere.

6. Results

The free parameters to be fitted to the COS UV spectra are equatorial SO$_2$ column density (or sub-solar SO$_2$ column density for the SIAM), SO$_2$ temperature, SO column density, and the surface reflectance spectrum. When fitting the 19 $\mu$m spectra, which are insensitive to SO, only the equatorial or sub-solar SO$_2$ column density and temperature are free parameters. When fitting UV surface reflectance spectrum, we assume that the surface albedo varies
smoothly with wavelength within each of the three wavelength stripes. Previous authors (e.g.: Trafton et al., 1996; McGrath et al., 2000) have used different methods to mitigate the effects of the broadband SO₂ surface frost albedo on the observed reflected spectra in this wavelength range. Given the uncertainty in the surface frost albedo, its spatial distribution on the surface and the fact that our HST disc-averaged observations cover narrow and discontinuous wavelength ranges, we have opted to use linear fits to the albedo within each wavelength range, to avoid the danger that higher-order polynomial fits to surface albedo will also attempt to match the SO₂ gas absorptions. This was similar to the approach taken by McGrath et al. (2000). In Section 7, we look at how higher-order polynomials change the best fits and retrieved values.

Initially, the only free parameter fitted was the equatorial SO₂ column density. The best-fit retrieved equatorial SO₂ column densities for both HST–COS and IRTF–TEXES are presented in Figs. 5 and 6, and Table 1. These results assume the modified latitude model, no SO column density and an atmospheric temperature held constant at 100 K for both wavelength regions for all locations. The 19 μm data shows the distinctive longitudinal variation discovered by Spencer et al. (2005), and confirmed by Feaga et al. (2009) and Tsang et al. (2012). The IR retrieved column densities increase from 0.23 (±0.15) × 10^{17} cm⁻² at lo central longitude 313° through to 1.71 (±0.13) × 10^{17} cm⁻² at longitude 155°. The analysis of our UV data shows the same longitudinal trend and comparable equatorial abundances, peaking at 151° west longitude with a density of 1.28 (±0.18) × 10^{17} cm⁻². The sub-solar longitudes for these observations are also given in Table 1.

For the HST–COS data, we investigated the effect on the spectral fits of including more free parameters in the fit. An example of this is shown in Fig. 7 for the spectrum taken at longitude 151°. Since the SO₂ bands are primarily in the shortest two wavelength strips, we have neglected the third strip in these plots. For the first case when temperature is held constant at 100 K and no SO is included, and the best-fit retrieved SO₂ column density is 1.28 (±0.18) × 10^{17} cm⁻², the 2200–2240 Å wavelength bands fit well, but the 2114 and 2120 Å band depths are not fitted well, with a reduced χ² value of 6.09. When atmospheric temperature becomes a free parameter, the reduced χ² value improves to 3.43 (at longitude 151°), and the retrieved SO₂ column abundance lowers to 1.08 (±0.16) × 10^{17} cm⁻², with no SO. The band depths at 2114 and 2120 Å are better fitted, with best-fit atmospheric temperature of 218 ± 32 K. With temperature as a free parameter, the SO₂ longitudinal variability remains (Fig. 8) and a correlation between

best-fit temperature and SO₂ column density is evident. Finally, the atmospheric temperature was held constant at 225 K (near the optimal temperature retrieved from the COS spectra alone) and SO₂ and SO column densities were allowed to vary. The reduced χ² value stayed at 3.44 for the same spectrum at 155° longitude. The magnitude of the SO₂ column abundance remains unaffected and the longitudinal variation remains, with no SO detected.

7. Discussion

When the IRTF–TEXES 19 μm observations and the HST–COS 2100 Å are analyzed together, assuming an atmosphere that follows the MLM distribution, and an isothermal atmospheric kinetic temperature of 100 K that does not vary with longitude, the retrieved sub-solar column densities of SO₂ and its longitudinal distribution agree with each other within the retrieved errors (Fig. 6). Both data sets indicate that during the 2010 epoch, the equatorial atmosphere column density peaks near 180° between 1.2 and 1.7 × 10^{17} cm⁻², decreasing towards the leading and trailing hemispheres to a minimum near 0.3 × 10^{17} cm⁻² near longitude 300 W. For an atmospheric temperature of 100 K, there is however a misfit of the SO₂ band shapes in the model spectra to the COS data between 2100 and 2130 Å (Fig. 7A) that appears at all longitudes. The misfit is lessened if a much higher gas temperature, over 200 K, is assumed (Fig. 7B). Warmer temperatures broaden the long-wavelength wings of the bands near 2102 and 2118 Å, improving the match to the shape of the spectrum. However, a mismatch is still evident at these higher temperatures at 2120 Å. We know from the analysis of the 19 μm observations that atmospheric kinetic temperatures are likely to be in the 110–160 K range, as higher temperatures produces poor fits in the mid-infrared. A similar mismatch appeared in high spectral resolution data from Trafton et al. (1996) where authors obtained spectra from 2097 to 2136 Å, at R ~ 6500 using the Goddard High Resolution Spectrograph (GHRS) on HST in 1992. The authors attributed the mismatch between their model and data in the 2114 and 2128 Å region to some unknown absorption across this region that is not gaseous SO₂. These authors excluded SO₂ frost as the source of the misfits. We note that although both we and Trafton et al. have trouble fitting Io spectra with SO₂ at these wavelengths, our observed Io spectra are different from Trafton et al. Our observed spectra have steeper wings between the continuum and the
Fig. 5. The inferred longitudinal distribution of Io’s atmosphere in 2010. Observed spectra are plotted in gray, with model fits shown in solid colors (red/blue), and the difference between the model and observations (residuals) in green. (Top) The SO$_2$ absorption bands as a function of Io longitude in the NUV as measured by HST–COS in September/October 2010. (Bottom) The non-LTE SO$_2$ bands, centered at 18.9 μm (530.4 cm$^{-1}$), from IRTF–TEXES on Mauna Kea (center). A Galileo-SSI map of Io taken through the red filter, overlaid with the sub-observer Io longitudes during the HST and IRTF observing campaigns. These inferred atmospheric densities use a constant atmospheric kinetic temperature of 100 K, assume the modified latitude model distribution for the atmosphere, and a linear variation of the UV surface albedo with wavelength for the COS spectra. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
absorption core at 2115 Å, which is more gradual in Trafton et al. (1996) from 2110 to 2115 Å. Our fitting problem is greatest in the core center at 2115 Å.

However, while the higher derived temperatures do produce better fits in this analysis of 2100 Å data, it is clear from Fig. 8 that the longitudinal variation in SO2 column density derived from the ultraviolet data is resilient against any uncertainty in atmospheric temperature (and SO column density). This indicates that the overriding sensitivity of the band depths in this 2100–2240 Å region is to SO2 column density and not temperature. The correlation of retrieved atmospheric temperature and abundance in Fig. 8B is striking; however, we refrain from concluding that there is a definitive correlation between atmospheric temperature and abundance or longitude because of the inconsistency between the UV and IR gas temperature retrievals discussed above. It is however interesting to note that one of the coldest temperatures detected is at the post-eclipse longitude 25 W, taken ~95 min after Io emerged from Jupiter’s shadow.

No definitive improvement in the reduced $\chi^2$ values was seen when adding SO to the fits. The fits are consistent with no SO in the atmosphere, with an upper limit of $3 \times 10^{13}$ cm$^{-2}$ across all longitudes, from the retrieved errors. This yields an upper limit on the SO/SO2 ratio of $\sim 2.7\%$, which is consistent with the 1–10% of SO/SO2 ratio found in previous works (e.g.: Jessup et al., 2004). However, because SO absorption data are only available at 300 K, as mentioned in Section 4 and shown in Fig. 3C, the model SO bands are broader than is probably the case on Io, where atmospheric temperatures are lower than 300 K. SO has an absorption band centered at 2120 Å (Fig. 3C), and it is conceivable, though not obvious, that addition of a narrower, lower-temperature, SO band could improve the fit to the observed spectrum near that wavelength (Fig. 7C). At present, our best solution is to fit the spectra at a relatively lower SO2 gas temperature of 225 K that is consistent with the best fit temperatures for the COS data alone (noting again that this is above the optimal 100 K to reconcile the IR and UV together). At 225 K, no effect of adding SO is noticed.

Another uncertainty associated with fitting the UV spectra is Io’s unknown surface reflectance signature. Io’s geometric albedo is both a function of the SO2 gas transmission and the surface reflectance. There are no independent constraints on the shape of Io’s surface reflectance signature at these wavelengths: the reflectance signature of pure SO2 frost is known (Nash et al., 1980; Hodyssey et al., 2013), but SO2 frost is not the only component on Io’s surface and so it cannot be assumed that the surface reflectance signature is that of pure SO2 frost. Therefore, it is interesting to investigate how changing the assumed shape of the underlying continuum surface reflectance changes the best fits and retrieved SO2 column densities. We initially set the coefficients used for the linear case and add higher order terms, allowing all orders to vary, to investigate the effect on the quality of fit and the retrieved column densities. Using orders 2, 3 and 4 produce minimized reduced $\chi^2$ values that are within 1% of order 1, which produced a column abundance of $1.28 \times 10^{17}$ cm$^{-2}$. The retrieved SO2 column abundances for these orders respectively were 1.26, 1.26 and 1.27 ($\times 10^{17}$ cm$^{-2}$). Therefore, we feel confident that using an order = 1 polynomial as our nominal case does not greatly affect the inferred gas abundances. The fitted order = 1 polynomials for the data are plotted in Figs. 5 (purple) and 7 (blue). The retrieved slopes of the frost albedos do not change much in longitude and in the narrow range of wavelengths sampled A similar discussion of the effects of the surface frost albedo on the overall ultraviolet spectrum at these wavelengths can be found in McGrath et al. (2000).

Finally, we investigated the effect on the retrieved UV and IR SO2 column densities when we change from the nominal modified latitude model (MLM) to the solar incidence angle model (SIAM). Moving from a modified latitude dependence to a solar incidence dependence requires the atmosphere to be more concentrated near the center of the disk, for a fixed disk-averaged column density. Fig. 9 shows the effect of the assumed distribution of the atmosphere on the retrieved sub-solar SO2 column densities as a function of Io longitude. For the IR, the SIAM (solid red) produces sub-solar column densities that are ~3 times greater than the MLM equatorial densities (dash red). For the UV, the SIAM (solid blue) produces sub-solar column densities between 4 and 5 times the MLM equatorial densities (dash blue). Under the SIAM, the column densities at longitude 151° (2100 Å) and 155° (19 μm) are between $5 \times 10^{17}$ cm$^{-2}$ and $8 \times 10^{17}$ cm$^{-2}$. The SIAM gives higher inferred peak densities for a given disk-integrated spectrum simply because it assumes that the atmosphere is more spatially concentrated on Io’s disk. The increase is smaller in the IR, because even in the MLM the disk-integrated IR spectrum (unlike the UV spectrum) is already weighted towards the disk center, where temperatures are highest and IR flux is greatest. However, other evidence favors the MLM, in particular Io’s appearance in reflected Ly-alpha light (Feldman et al., 2000), where the bright poles and limb-to-limb darkness at low latitude (due to SO2 gas absorption) suggest that atmospheric density is controlled more strongly by latitude than by solar incidence angle alone. In addition, the sub-solar densities inferred from the SIAM are much higher than determined from disk-resolved observations (Feaga et al., 2009; Jessup et al., 2004; McGrath et al., 2000), which are much more consistent with our MLM-derived abundances.

To conclude, the combined analysis of the HST–COS 2100 Å data with those from IRTF–TEXES at 19 μm is a powerful technique to test different distributions and assumptions of Io’s atmosphere. The fact, confirmed by the current analysis, that the atmosphere appears to vary little with local time, but varies dramatically with latitude, places strong constraints on atmospheric support mechanisms. An atmosphere in instantaneous vapor pressure equilibrium with low thermal inertia frost, which is itself in instantaneous thermal equilibrium with sunlight, would produce an atmospheric

![Fig. 6. Retrieved sub-solar SO2 column densities vs. longitude for both HST–COS (blue cross, dashed errors), and IRTF–TEXES observations (red diamonds, dotted errors). Four months separate the IRTF and HST observations. SO2 kinetic temperatures have been fixed at 100 K and the errors have been calculated using the Monte Carlo method. No SO has been added to the synthetic spectra for the fits. The derived column densities from the two wavelength regions are consistent given the estimated uncertainties. These inferred atmospheric densities are derived from the modified latitude model, where the atmospheric density falls off towards the poles, but the density is constant in local time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
Fig. 7. Variation of the spectral fit quality of HST–COS data of the first two stripes at Io longitude of 151°W with different fitted parameters. Observed spectra (black) are compared to the best-fit model spectra (red). Surface albedo (blue) and residuals (green) are also shown. (A) $\text{SO}_2$ temperature fixed at 100 K, $\text{SO}_2$ column density fixed at 0 cm$^{-2}$ and $\text{SO}_2$ column density is varied. (B) $\text{SO}_2$ column density fixed at 0 cm$^{-2}$, $\text{SO}_2$ temperature and $\text{SO}_2$ column density are varied. (C) $\text{SO}_2$ temperature fixed at 225 K, $\text{SO}_2$ and $\text{SO}$ column densities are varied. Adding $\text{SO}$ (yellow) produces no improvements on the fits. Reduced $\chi^2$ and retrieved variables are printed for these best-fit model spectra. The MLM was used in this case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 8. The longitudinal distribution of the retrieved variables in this study from HST–COS spectra, with retrieved atmospheric temperature (red), SO$_2$ (blue) and SO column densities (green). The results show when (A) the SO$_2$ column density is varied, atmospheric temperature and SO column densities held constant, (B) temperature is allowed to vary and (C) when SO column density is allowed to vary. The longitude distribution of the SO$_2$ column density is only weakly dependent on the other variables. The MLM model was used in these cases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
abundance depending primarily on solar incidence angle, which can be strongly ruled out by available data. Atmospheric support primarily by low-latitude volcanoes, or by high thermal inertia frost that varies little in temperature with time of day, or a combination of these two (Tsang et al., 2012), provides a better fit to the data. Rotation effects and winds will also affect the longitudinal distribution (Walker et al., 2012).

8. Conclusions

Contemporaneous observations of Io’s atmosphere were obtained in 2010 from the mid-infrared and the mid-ultraviolet and analyzed together using a common model of the Io atmosphere. The longitudinal distribution of Io’s SO$_2$ atmosphere as observed by mid-IR and Ly-$\alpha$ has been confirmed in the mid-UV for the first time. Assuming our “modified latitude model” in which density depends primarily on latitude rather than local time, the SO$_2$ equatorial column densities and their longitudinal variability derived from the 19 $\mu$m IRTF–TEXES data and the 2100 Å HST–COS data agree with each other to within errors, Io’s inferred equatorial atmospheric density during the 2010 epoch varies from a minimum of 0.3 $\times$ 10$^{17}$ cm$^{-2}$ at 330 W to a maximum between 1.2 $\times$ 10$^{17}$ cm$^{-2}$ (UV) and 1.7 $\times$ 10$^{17}$ cm$^{-2}$ (IR) near 150 W. Using the HST–COS data, no evidence for SO was found, placing an upper limit of 3 $\times$ 10$^{15}$ cm$^{-2}$ at all longitudes from the retrieved errors, giving a SO/SO$_2$ ratio upper limit of 2.7%. However, higher best-fit atmospheric temperatures ($\sim$200 ± 50 K) were derived from the UV than from the IR ($\sim$110 ± 20 K, Tsang et al., 2012). We also show that the peak atmospheric density is sensitive to the spatial distribution of Io’s atmosphere that we assume in the disk-averaged model, and the modified latitude model, where the density is a function of latitude but not solar incidence angle, gives peak densities that are much more consistent with previous estimates of atmospheric density than a model in which density varies with solar incidence angle.

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