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

Constantine C.C. Tsang *, John R. Spencer, Kandis Lea Jessup

Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, 80302 CO, USA

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ABSTRACT

We report on mid-UV spectroscopy of Io's SO_2 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 SO_2 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 SO_2 column density, temperature, and SO abundance as variables. Equatorial SO_2 column densities of between 0.26 and 1.28×10^{17} cm^{-2} were derived, depending on Io's central longitude. We compare these results with disk-averaged 19 μm mid-IR spectroscopy in thermal emission from the NASA Infrared Telescope Faculty, taken at multiple central longitudes only four months prior to the mid-UV observations. The derived SO_2 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-α 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 SO_2 frost, with column abundance thus depending only 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.

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 (SO_2) dominated atmosphere, with sub-solar column densities in the $\sim10^{17}$ cm^{-2} range (Spencer et al., 2005), and a surface pressure of ∼ a few nbar (Lellouch et al., 2007). SO_2 frost is thought to originate from the condensation of gas released from Io's SO_2 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).

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* Corresponding author. Fax: +1 303 546 9687.
E-mail address: con@boulder.swri.edu (C.C.C. Tsang).

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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 Iogenic 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 SO_2 column abundance in the $\sim 10^{16}\,\text{cm}^{-2}$ 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 7×10^{15} and $3.5 \times 10^{16}\,\text{cm}^{-2}$, a factor of five difference between the densest and least dense locations, indicating a high degree of spatial variation of the atmosphere. The SO_2 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-α by finding the atmospheric density decreasing from the equator (with a sub-solar column density of $1.5 \times 10^{17}\,\text{cm}^{-2}$) towards the poles ($2\text{–}3 \times 10^{16}\,\text{cm}^{-2}$ 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-α light, but much darker at low latitudes. This was attributed to an atmosphere predominantly located at low latitudes that absorbs Lyman-α light. The poles, having less atmosphere, appeared brighter as Lyman-α light is reflected back with minimal attenuation. The Lyman-α 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 volcanoes (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-solar column abundance between 1.4 and $4.5 \times 10^{16}\,\text{cm}^{-2}$. Feaga et al. (2009) used HST–STIS imaging observations of Lyman-α spanning five years to measure the longitudinal variability of the atmospheric SO_2 distribution on Io. The maximum average dayside sub-solar SO_2 column density they detected was $\sim 5 \times 10^{16}\,\text{cm}^{-2}$ near 140° longitude; the minimum average dayside density of $1.5 \times 10^{16}\,\text{cm}^{-2}$ 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 SO_2 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 Faculty (IRTF) with the Texas Echelon Cross Echelle Spectrograph (TEXES) spectrograph (Lacy et al., 2002). The 19 μm non-local thermal equilibrium absorption bands of SO_2 were fitted to retrieve equatorial SO_2 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 ($1.5 \times 10^{16}\,\text{cm}^{-2}$) were less than the anti-jovian hemisphere values ($1.5 \times 10^{17}\,\text{cm}^{-2}$), 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 $1.12 \times (\pm 0.134)\ 10^{17}\,\text{cm}^{-2}$ in 2001 to $0.61\ (\pm 0.145) \times 10^{17}\,\text{cm}^{-2}$ in 2005, near aphelion. The atmospheric density then rose to $1.51\ (\pm 0.215) \times 10^{17}\,\text{cm}^{-2}$ 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 SO_2 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 ∼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 SO_2 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.