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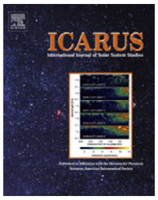

Io's atmosphere: Constraints on sublimation support from density variations on seasonal timescales using NASA IRTF/TEXES observations from 2001 to 2010

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ABSTRACT

We present an analysis of 19 μm spectra of Io's SO_2 atmosphere from the TEXES mid-infrared high spectral resolution spectrograph on NASA's Infrared Telescope Facility, incorporating new data taken between January 2005 and June 2010 and a re-analysis of earlier data taken from November 2001 to January 2004. This is the longest set of contiguous observations of Io's atmosphere using the same instrument and technique thus far. We have fitted all 16 detected blended absorption lines of the ν_2 SO_2 vibrational band to retrieve the subsolar values of SO_2 column abundance and the gas kinetic temperature. By incorporating an existing model of Io's surface temperatures and atmosphere, we retrieve sub-solar column densities from the disk-integrated data. Spectra from all years are best fit by atmospheric temperatures <150 K. Best-fit gas kinetic temperatures on the anti-Jupiter hemisphere, where SO_2 gas abundance is highest, are low and stable, with a mean of 108 (±18) K. The sub-solar SO_2 column density between longitudes of 90–220° varies from a low of 0.61 (±0.145) $\times 10^{-17}$ cm^{-2}, near aphelion in 2004, to a high of 1.51 (±0.215) $\times 10^{17}$ cm^{-2} in 2010 when Jupiter was approaching its early 2011 perihelion. No correlation in the gas temperature was seen with the increasing SO_2 column densities outside the errors.

Assuming that any volcanic component of the atmosphere is constant with time, the correlation of increasing SO_2 abundance with decreasing heliocentric distance provides good evidence that the atmosphere is at least partially supported by frost sublimation. The SO_2 frost thermal inertias and albedos that fit the variation in atmospheric density best are between 150–1250 W m^{-2} s$^{-1/2}$ K^{-1} and 0.613–0.425 respectively. Photometric evidence favors albedos near the upper end of this range, corresponding to thermal inertias near the lower end. This relatively low frost thermal inertia produces larger amplitude seasonal variations than are observed, which in turn implies a substantial additional volcanic atmospheric component to moderate the amplitude of the seasonal variations of the total atmosphere on the anti-Jupiter hemisphere. The seasonal thermal inertia we measure is unique both because it refers exclusively to the SO_2 frost surface component, and also because it refers to relatively deep subsurface layers (few meters) due to the timescales of many years, while previous studies have determined thermal inertias at shallower levels (few centimeters), relevant for timescales of ~2 h (eclipse) or ~2 days (diurnal curves).

1. Introduction

The jovian moon Io sustains a tenuous atmosphere due ultimately to the intense volcanic activity caused by tidal heating. The atmosphere predominantly consists of SO_2 (Pearl et al., 1979) along with smaller amounts of SO (Lellouch et al., 1996; McGrath et al., 2000), S_2 (Spencer et al., 2000) and other trace species such as NaCl (Lellouch et al., 2003). The loss of this atmosphere into the jovian magnetosphere affects the entire jovian system, making Io's one of the most fascinating atmospheres in our Solar System. The Io atmosphere allows us to study unique physical processes, adding to our understanding of basic atmospheric physics and surface–atmosphere interactions. A comprehensive review of Io and its atmosphere can be found in Lellouch et al. (2007) and McGrath et al. (2004).

The first detection of an atmosphere around Io was made by Voyager/IRIS 7.3 μm spectra, which detected SO_2 at Loki Patera

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Table 1
Data from observations made from IRTF/TEXES between 2005 and 2010. Data on observations made from 2001 to 2004 can be found in Spencer et al. (2005).

UT Date (YYMMDD)	Io central longitude (°W)	Radial velocity (km s^{-1})	Io mean airmass	Callisto airmass	Heliocentric distance (AU)	Fitted 530.42 cm^{-1} line depth
050116	253	−11.3	1.16	1.18	5.45	0.0134
050117	105	−44.3	1.19	1.15	5.45	0.0420
050117	112	−43.6	1.13	1.11	5.45	0.0407
050118	302	−12.9	1.14	1.11	5.45	−0.0127
050119	151	−36.0	1.17	1.13	5.45	N/A
050119	159	−33.6	1.16	1.11	5.45	N/A
050120	339	−21.3	1.63	1.21	5.45	N/A
050120	341	−22.1	1.54	1.21	5.45	N/A
070414	324	−13.1	1.40	1.30	5.33	0.0100 ± 0.0055
070414	336	−16.2	1.36	1.60	5.33	0.0074 ± 0.0047
070415	164	−27.8	1.44	1.55	5.33	0.0451 ± 0.0055
070417	213	−13.1	1.39	1.40	5.33	0.0450 ± 0.0052
070418	067	−38.1	1.36	1.35	5.33	0.0300 ± 0.0038
070418	077	−38.8	1.50	1.35	5.33	0.0353 ± 0.0057
070419	273	−4.5	1.35	1.50	5.33	0.0140 ± 0.0084
090602	216	−16.5	1.63	1.75	5.06	0.0559 ± 0.0052
090602	218	−15.8	1.51	1.60	5.06	0.0587 ± 0.0060
090602	223	−14.8	1.37	1.30	5.06	0.0569 ± 0.0059
090602	226	−14.2	1.31	1.30	5.06	0.0517 ± 0.0044
090604	264	−9.16	1.52	1.65	5.06	0.0356 ± 0.0045
090604	272	−8.95	1.29	1.40	5.06	0.0306 ± 0.0042
090604	282	−9.17	1.19	1.20	5.06	0.0293 ± 0.0045
090605	106	−42.9	1.56	1.70	5.06	0.0632 ± 0.0061
090605	113	−42.11	1.34	1.35	5.06	0.0542 ± 0.0049
090605	116	−41.71	1.28	1.25	5.06	0.0571 ± 0.0048
090605	123	−40.56	1.20	1.25	5.06	0.0593 ± 0.0033
090607	156	−32.98	1.41	1.60	5.06	0.0720 ± 0.0037
090607	164	−30.46	1.24	1.35	5.06	0.0677 ± 0.0042
090609	201	−19.30	1.42	1.33	5.06	0.0633 ± 0.0043
090609	210	−16.90	1.25	1.21	5.06	0.0581 ± 0.0048
090609	219	−14.32	1.19	1.20	5.06	0.0564 ± 0.0061
100531	269	−8.29	1.37	1.46	4.97	0.0312 ± 0.0098
100601	112	−41.44	1.34	1.39	4.97	0.0600 ± 0.0113
100602	313	−14.23	1.43	1.19	4.97	0.0234 ± 0.0049
100603	155	−31.34	1.21	1.23	4.96	0.0791 ± 0.0051
100605	205	−17.82	1.31	1.19	4.96	0.0782 ± 0.0059
100607	247	−9.58	1.51	1.58	4.96	0.0547 ± 0.0087

(Pearl et al., 1979). Since then, numerous studies have further elucidated the quantity and distribution of atmospheric SO$_2$, with initial detections being made (i) at ultraviolet wavelengths between 0.2 and 0.4 µm (Ballester et al., 1990), (ii) from images of Io in reflected HI Lyman-α light (Feldman et al., 2000), (iii) at 19 µm in the mid-infrared (Spencer et al., 2005) and (iv) using emission lines at millimeter wavelengths (Lellouch et al., 1990). Recently, SO$_2$ absorption features have also been detected at 4 µm (Lellouch et al., 2009). Much subsequent work has expanded on these initial observations and interpretations.

The equatorial SO$_2$ column density is in the range 1.5×10^{16}–1.5×10^{17} cm^{-2} (McGrath et al., 2000; Jessup, 2002; Jessup et al., 2004; Spencer et al., 2005; Feaga et al., 2009). Atmospheric pressure varies dramatically with both longitude (McGrath et al., 2000; Jessup et al., 2004; Spencer et al., 2005) and perhaps also with time (Trafton et al., 1996; Jessup, 2002). However, the nature and causes of these variations, and the relative roles of volcanism and frost sublimation in maintaining the tenuous atmosphere, are still poorly understood (Ingersoll, 1989; Strobel and Wolven, 2001; Jessup et al., 2004; Saur and Strobel, 2004; Moullet et al., 2008; Walker et al., 2010). There is strong evidence for dominant sublimation support from changes in Io's neutral O and S emissions during Jupiter eclipse (Saur and Strobel, 2004; Retherford et al., 2007), and from the latitudinal distribution of the atmosphere seen by Hubble Space Telescope (HST) (Jessup et al., 2004). However, there is also evidence for dominant direct volcanic support, including the dawn-to-dusk persistence of the atmosphere seen in HST Ly-α images (Strobel and Wolven, 2001; Feaga et al., 2009). In this work, we investigate the long-term trends in atmospheric temperature and density to determine the relative roles of sublimation and volcanic support from 19 µm thermal infrared data.

Here we present a new approach in studying the 19 µm spectrum. Instead of deriving SO$_2$ column densities by measuring solely the depth of the strongest observed line at 530.41 cm^{-1}, requiring assumptions of the modeled mean kinetic gas and surface temperatures (Spencer et al., 2005), we instead make use of the entire spectrum and its multiple SO$_2$ absorption lines. Because the spectrum's shape and line depths are sensitive to different parameters, we can independently retrieve gas temperature and column abundance with minimal external assumptions.

A major goal of our long-term observation program has been to quantify the degree to which, if at all, the atmosphere of Io might respond to the increase in solar flux as Jupiter (and thus Io) approaches perihelion in 2011. At an aphelion distance of 5.46 AU, Jupiter receives 45.9 W m^{-2} of solar radiation. When it reaches perihelion however, the distance of Jupiter from the Sun has closed to 4.95 AU and the solar flux increases to 55.9 W m^{-2}, an increase of more than 20%. This increased heating should drive more SO$_2$ frost on the surface of Io to sublimate, given the strong dependence of vapor pressure on temperature, and thereby increase the density of the atmosphere, if atmospheric support by frost sublimation is important. Here, we investigate whether atmospheric density variability is linked to heliocentric distance and whether there is any relation with atmospheric temperature. We also model the contribution of any sublimation component to the overall density of the Ionian atmosphere relative to direct volcanic support.