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## RESEARCH ARTICLE

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## Key Points:

- Io's atmosphere observed by Gemini-TEXES at 19  $\mu\text{m}$
- SO<sub>2</sub> band depths drop significantly in Jupiter eclipse
- Modeling indicate primary, molecular atmosphere has collapsed, indicating ice sublimation support

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## The collapse of Io's primary atmosphere in Jupiter eclipse

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**Abstract** Volcanic outgassing due to tidal heating is the ultimate source of a tenuous SO<sub>2</sub> atmosphere around Jupiter's moon Io. The question of whether SO<sub>2</sub> frost on the surface plays a part, and to what degree, in maintaining Io's atmosphere with the constant volcanic outgassing is still debated. It is believed that for a sublimation-supported atmosphere, the primary atmosphere should collapse during eclipses by Jupiter, as the SO<sub>2</sub> vapor pressure is strongly coupled to the temperature of the ice on the surface. No direct observations of Io's atmosphere in eclipse have previously been possible, due to the simultaneous need for high spectral and time sensitivity, as well as a high signal-to-noise ratio. Here we present the first ever high-resolution spectra at 19  $\mu\text{m}$  of Io's SO<sub>2</sub> atmosphere in Jupiter eclipse from the Gemini telescope. The strongest atmospheric band depth is seen to dramatically decay from  $2.5 \pm (0.08)\%$  before the eclipse to  $0.18 \pm (0.16)\%$  after 40 min in eclipse. Further modeling indicates that the atmosphere has collapsed shortly after eclipse ingress, implying that the atmosphere of Io has a strong sublimation-controlled component. The atmospheric column density—from pre-eclipse to in-eclipse—drops by a factor of  $5 \pm 2$ .

## 1. Introduction

Io is host to a spatially inhomogeneous and tenuous atmosphere of neutral SO<sub>2</sub>, the ultimate byproduct of extensive and long-lived volcanism on its surface [Pearl *et al.*, 1979; Lellouch, 1996; Lellouch *et al.*, 2007]. The atmosphere is unique in our Solar System for its particular interaction with volcanic plumes and the ice that forms on the surface as a consequence of gas plume condensation. Notable other species from outgassing include SO and NaCl, as well as SO<sub>2</sub> [e.g., Moullet *et al.*, 2010].

The exact nature and the mechanisms for supporting this atmosphere are still strongly debated and at times contradictory. The atmospheric density varies with geographic location, with the densest part located on the anti-Jupiter hemisphere, and these variations are larger than diurnal variations [Jessup and Spencer, 2015], implying minimal sublimation support. Studies measuring the dependence of a sublimation supported atmosphere with latitude have proved inconclusive [Feldman *et al.*, 2000; Jessup *et al.*, 2004; Feaga *et al.*, 2009]. Although an equator-to-pole decrease in SO<sub>2</sub> density is observed, this can be attributed to more volcanic centers near the equator. Correlations of Io's atmosphere with the positions of volcanoes as well as the longitudinal distribution of SO<sub>2</sub> ice have been equally ambiguous [Feaga *et al.*, 2009; Spencer *et al.*, 2005]. Observations of far ultraviolet atomic emissions from Io's near-surface and extended atmosphere seem to support the sublimation hypothesis [Clarke *et al.*, 1994; Wolven *et al.*, 2001; Retherford *et al.*, 2007; Roth *et al.*, 2011]. A mixture of both sublimation and volcanic support is suggested by a seasonal dependency of the atmospheric density over the Jupiter year [Tsang *et al.*, 2012].

If the predominately SO<sub>2</sub> atmosphere is in vapor pressure equilibrium with the large reservoir of SO<sub>2</sub> ice that covers much of Io's surface, as Io enters eclipse and is no longer heated by the Sun, the decreasing surface temperatures will cause the primary atmosphere to collapse out onto the surface [Saur and Strobel, 2004]. The atmosphere, with a scale height of 10 km, would transition from a collisionally thick atmosphere, with a mean free path ( $\lambda$ ) = 1 m, to an exospheric atmosphere ( $\lambda$  ~100 km). Conversely, if the atmosphere remains constant during eclipse, it would point to a volcanically supported atmosphere. Observations of Io's surface have shown a decrease in its thermal emission during such eclipse events [Sinton and Kaminski, 1988]. However, direct observations of the primary atmosphere under eclipse conditions have been difficult to obtain due to the need for spectral resolutions, signal-to-noise ratios (SNR), and time resolutions sufficiently high to resolve the atmosphere's response in eclipse.

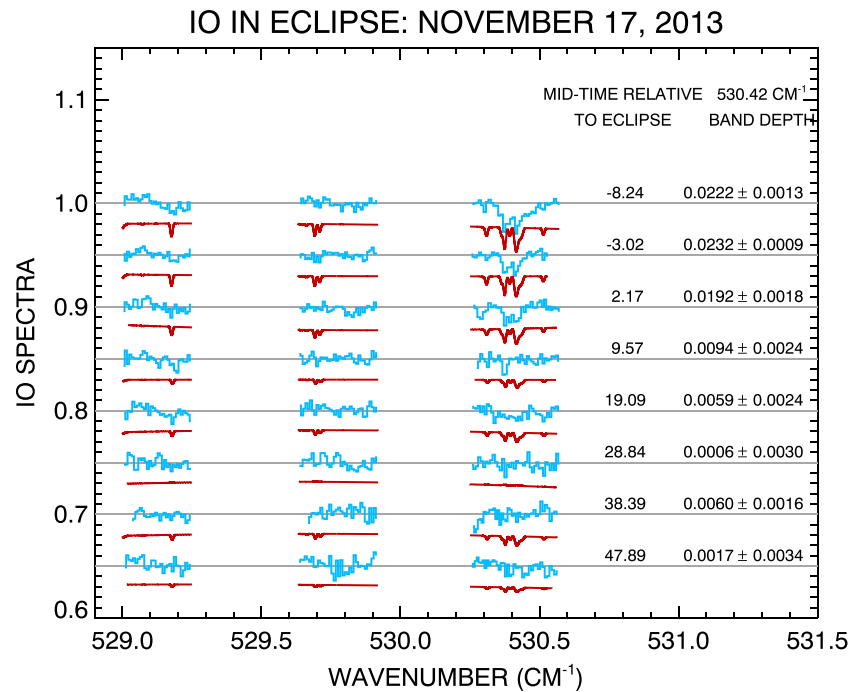
**Table 1.** Observation Log of the Io Eclipse Observations From Gemini-TEXES

Spectrum Number + Phase	Starting Time (UT)	Ending Time (UT)	Middle Time (UT)	Time Relative to Jupiter Eclipse Ingress (min)	Middle Time Io Central Meridian Longitude ( $^{\circ}$ )	Continuum SNR	Air Mass	530.42 $\text{cm}^{-1}$ Band Depth (%)
<i>Date: 17 November 2013</i>								
1 Sunlit	11:02	11:06	11:04	-8.24	340.9	188	1.34	2.22 $\pm$ 0.13
2 Sunlit	11:07	11:11	11:09	-3.02	341.6	187	1.32	2.32 $\pm$ 0.09
3 Ingress	11:12	11:16	11:14	2.17	342.3	146	1.30	1.92 $\pm$ 0.18
4 Eclipse	11:17	11:26	11:21	9.57	343.3	145	1.27	0.94 $\pm$ 0.24
5 Eclipse	11:27	11:36	11:31	19.09	344.7	126	1.23	0.59 $\pm$ 0.24
6 Eclipse	11:36	11:45	11:40	28.84	345.9	118	1.20	0.06 $\pm$ 0.30
7 Eclipse	11:46	11:55	11:50	38.39	347.4	118	1.17	0.60 $\pm$ 0.16
8 Eclipse	11:56	12:04	12:00	47.89	349.4	102	1.14	0.17 $\pm$ 0.34
<i>Date: 24 November 2013</i>								
1 Sunlit	12:22	12:27	12:25	-41.33	337.2	385	1.03	2.52 $\pm$ 0.07
2 Sunlit	12:28	12:32	12:30	-36.05	337.9	299	1.03	2.44 $\pm$ 0.09
3 Sunlit	12:33	12:38	12:35	-30.64	338.6	349	1.03	2.34 $\pm$ 0.09
4 Sunlit	12:39	12:43	12:41	-25.00	338.4	359	1.02	2.55 $\pm$ 0.08
5 Sunlit	12:44	12:49	12:46	-19.66	340.1	346	1.02	2.30 $\pm$ 0.07
6 Sunlit	12:49	12:54	12:51	14.41	340.8	313	1.01	2.59 $\pm$ 0.01
7 Sunlit	12:55	13:00	12:57	-8.66	341.7	289	1.01	2.72 $\pm$ 0.08
8 Sunlit	13:01	13:03	13:01	-2.00	342.3	354	1.01	2.98 $\pm$ 0.01
9 Ingress	13:03	13:06	13:04	1.00	342.7	199	1.01	1.76 $\pm$ 0.01
10 Ingress	13:06	13:09	13:07	4.00	343.1	137	1.01	1.73 $\pm$ 0.02
11 Eclipse	13:10	13:19	13:14	8.81	344.1	234	1.01	0.67 $\pm$ 0.01
12 Eclipse	13:20	13:29	13:24	18.38	345.5	144	1.00	0.37 $\pm$ 0.02
13 Eclipse	13:30	13:39	13:34	28.19	346.9	157	1.00	0.42 $\pm$ 0.02
14 Eclipse	13:40	13:49	13:44	38.43	348.3	100	1.00	-0.07 $\pm$ 0.05
15 Eclipse	13:50	13:58	13:54	47.88	349.7	77	1.01	0.18 $\pm$ 0.04

Here we present observations of the primary  $\text{SO}_2$  atmosphere of Io as it enters eclipse by Jupiter. The atmosphere appears in absorption at 19  $\mu\text{m}$ , where multiple  $\text{SO}_2$   $\nu_2$  vibrational bands exist, most notably a blend of lines near 530.42  $\text{cm}^{-1}$  [Spencer et al., 2005; Tsang et al., 2012]. These rotation-vibration lines always appear in absorption as the atmosphere with cold vibrational temperatures is heated from below by a warm surface from a combination of solar heating and heating by volcanoes. The low density of the atmosphere results in longer collisional timescales compared to its radiative timescales, resulting in an atmosphere that is in nonlocal thermodynamical equilibrium (non-LTE) with its kinetic temperature ( $T_K$ ) [Lellouch et al., 1992]. The observation of the decay of both the atmospheric absorption bands and the thermal flux, before and during eclipse, allows us to elucidate on the nature of the atmosphere in eclipse.

## 2. Observations

Observations were taken with the 8 m Gemini-north telescope using the Texas Echelon Cross Echelle Spectrograph (TEXES) [Lacy et al., 2002]. These observations occurred over two nights, 17 and 24 November 2013 when Io was at a heliocentric distance of 5.17 AU. The observational details are provided in Table 1. Io was observed during both occasions as it crossed from being sunlit into Jupiter's shadow, from 40 min prior to eclipse ingress to 50 min post-ingress, with high time resolutions between 5 and 10 min per integration. Io subtended 1.1 arc sec in the sky on both nights. TEXES was used in high spectral resolution mode resulting in spectra centered at a wave number of 529.79  $\text{cm}^{-1}$  with spectral resolution of approximately 67,000. These settings allowed us to cover seven blended  $\text{SO}_2$  absorption features, with gaps in between the echelon grating orders (Figures 1 and 2) at the highest possible spectral resolution in order to resolve the absorption features. The spectrometer slit was placed in the north-south direction on Io, with a length and width of 8 arc sec and 0.75 arc sec, respectively. Targets were nodded along the slit to remove thermal background contributions. The moon Callisto was used as our calibration target due to being spectrally bland in this wavelength range, being brighter than Io, and due to its similar air mass through the observation period: spectra were divided by Callisto to remove telluric and instrumental features. Times and air masses of each spectra on both nights can be found in Table 1. The continuum of all the Io spectra was flattened by taking a number of points in the spectrum that do not have  $\text{SO}_2$  absorption and



**Figure 1.** Gemini-TEXES spectra of Io from the 17 November 2013 disappearance event. Observations (blue) are separated between 5 and 10 min, plotted with offsets, and compared to spectra generated by a radiative transfer model (red).

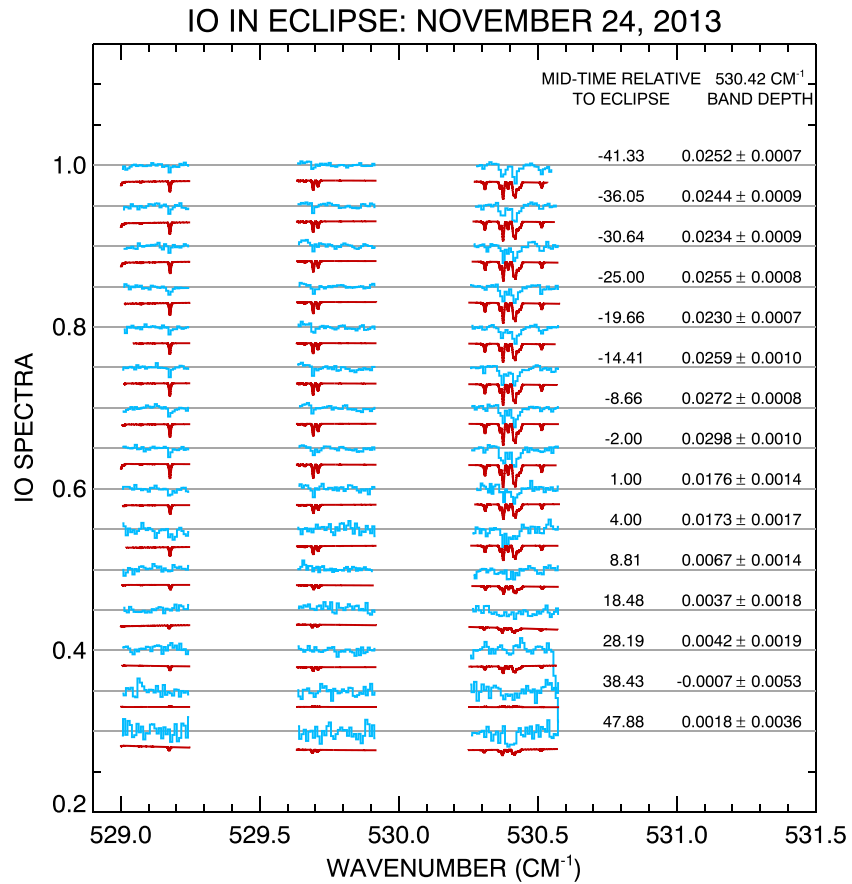
fitting a fourth-order polynomial. This removes any spectral sagging that might be present. Eclipse ingress begins when part of Io's disk enters Jupiter shadow. It takes 4 min for Io to be completely eclipsed by Jupiter. We define the eclipse middle time as the halfway point between Io being fully in sunlight and fully in Jupiter shadow. The observed mid-times are taken from the TEXES data headers, while the time of eclipse ingress is taken from the HORIZONS ephemeris database.

Io's thermal emission at 19  $\mu\text{m}$  drops by a factor of 3.25 (Figure 3) by the end of the observing sequence compared to its flux at start of the eclipse. Some slit loss is expected, but tracking on Io was well maintained on both occasions. Errors in the band depth were determined using a Monte Carlo approach where the measured noise in the spectrum was added to the best fit spectrum and band depths determined again. This process was done 50 times. The depths of the atmospheric absorption features were measured by fitting these observations with a synthetic spectrum generated by a radiative transfer model. All band depths were seen to drop significantly after eclipse ingress for both observations, including the main set of blended lines at 530.42  $\text{cm}^{-1}$ , from 2.5 ( $\pm 0.08$ )% depth pre-eclipse to 0.18  $\pm$  (0.16)% depth after 40 min, a factor of approximately 14 compared to pre-eclipse.

These are the first observations of Io's primary SO<sub>2</sub> atmosphere in Jupiter eclipse and initially, with the measurements of the SO<sub>2</sub> band depths alone, it would seem to indicate a collapsing atmosphere. However, the situation is complicated by the dependence of these band depths with the temperature of the atmosphere and that of the surface. We now begin a thorough analysis to take these variables into account to arrive at a solution for the atmospheric state in eclipse.

### 3. Radiative Transfer Model

Synthetic spectra were calculated for the SO<sub>2</sub>  $\nu_2$  vibrational bands seen in these 19  $\mu\text{m}$  observations. The radiative transfer model utilizes the Curtis Matrix method and described at length in López-Puertas and Taylor [2001] and López-Valverde and López-Puertas [1994]. The non-LTE model was used by Spencer *et al.* [2005] and Tsang *et al.* [2012, 2013] to analyze the same SO<sub>2</sub> 19  $\mu\text{m}$  (530.42  $\text{cm}^{-1}$ ) absorption features to look for seasonal effects and longitude variations on Io. The SO<sub>2</sub> line list is provided by HITRAN2K and amended by Flaud *et al.* [1993] and described in Spencer *et al.* [2005]. The Voigt line shape is used, which is valid at these

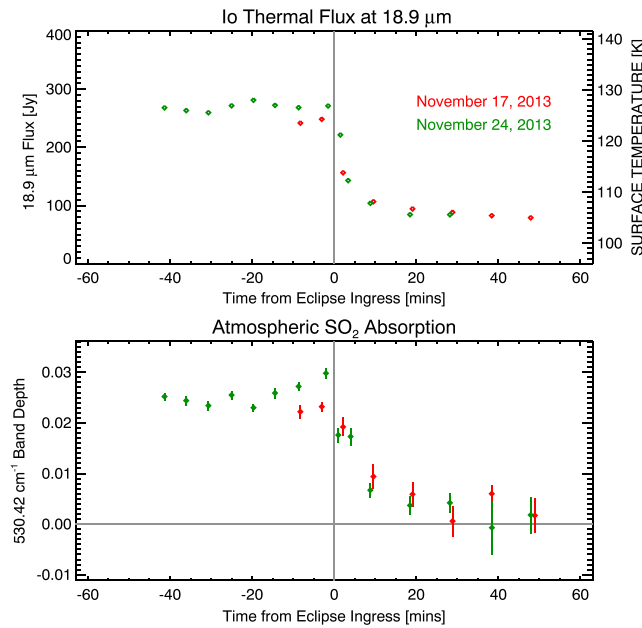


**Figure 2.** Time resolved Io SO<sub>2</sub> absorption spectra from 529.0 to 530.6 cm<sup>-1</sup> from Gemini-TEXES. We plot the Gemini-TEXES Io spectra (blue) during eclipse ingress on 24 November 2013. Each spectrum is offset vertically by 0.05. Observations were summed in 5 to 10 min increments at a resolution of ~67,000. The main 530.42 cm<sup>-1</sup> SO<sub>2</sub> absorption feature can be readily seen prior to eclipse. A radiative transfer model is used to fit for the depth of the absorption feature (red). This and other SO<sub>2</sub> features decrease in strength as the eclipse proceeds.

low densities and far  $\nu_2$  line spacings. The radiative transfer model considers the spontaneous and stimulated emission of the (010–000) fundamental band, absorption of upwelling thermal flux from Io’s surface and exchanges between layers. The atmospheric vertical temperature profile is assumed to be isothermal. All parameters are spatially invariant. This simplification is reasonable because the retrieved SO<sub>2</sub> column density from the radiative transfer model used here is very similar to the values retrieved for modeled distributions of atmospheric density at these longitudes [Tsang et al., 2013]. Model spectra are calculated from the surface to 200 km in altitude (20 times the scale height of ~10 km) and assume the entire atmosphere is composed of SO<sub>2</sub>.

#### 4. Modeling Surface and Atmospheric Temperatures

Previous modeling of the photochemistry and vertical transport of SO<sub>2</sub> in Io’s atmosphere showed the radiative timescale of Io’s primary atmosphere responding to a change in insolation is ~10<sup>3</sup> s [Strobel et al., 1994]. This is on the same timescale as our observations of SO<sub>2</sub> density (N<sub>SO2</sub>) in eclipse and much longer than the timescale for sublimation and condensation to affect the SO<sub>2</sub> atmosphere (~100 s, Summer and Strobel [1996]), allowing us to study and model the atmospheric response in eclipse. The observed decrease in the SO<sub>2</sub>  $\nu_2$  vibrational bands needs to be understood in the context of the changes in surface temperature ( $T_{SURF}$ ) and atmospheric kinetic temperature ( $T_{ATM}$ ) before any conclusions of the atmospheric response in eclipse can be made, because band depth depends on these temperatures as well as on column abundance [Spencer et al., 2005; Tsang et al., 2012].



**Figure 3.** (top) The thermal flux of Io and (bottom) the SO<sub>2</sub> absorption depth at 530.42 cm<sup>-1</sup> as a function of time relative to Jupiter eclipse. The thermal flux at 19 μm drops by a factor of 3.25 in 30 min as Io cools in eclipse. The atmospheric absorption drops by a factor of ~14 in the same period. The last two flux points on 24 November have been omitted in this plot, as guiding on Io was lost. We use the fluxes from 17 November for those missing flux measurements. The last band depth value on 17 November has been shifted by 1 min for clarity.

determined photometric fluxes of Io [Sinton and Kaminski, 1988] at 20 μm prior to eclipse ingress (at the same longitudes on Io) and converted those thermal fluxes to a reference wavelength of 19 μm using the Planck function. We then normalized our fluxes and converted them into a brightness temperature using the Planck function. We assume that the brightness temperature is the surface temperature of Io and the majority of the thermal flux is from the passive body of Io that drives ice sublimation. This is reasonable because if the atmosphere was global in extent but the volcanic thermal emissions were significant, the much higher volcanic temperatures (perhaps on the order of ~300 K cf. to the passive surface temperature of ~110 K) would dominate in eclipse. In this limiting case, the SO<sub>2</sub> band depths would therefore increase in eclipse, as the passive emission decreases while the hotter volcanic emissions stay constant. The fact we see the band depths decrease in eclipse requires the atmosphere to have collapsed (as shown in section 5).

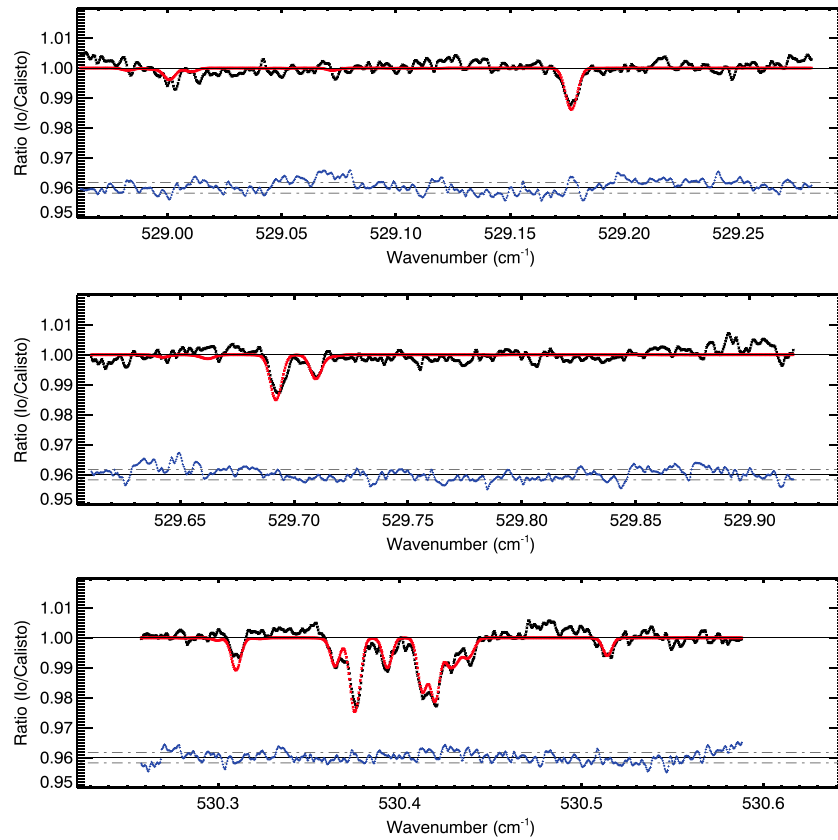
**4.2. Modeling T<sub>ATM</sub>**

The gas kinetic temperature (T<sub>ATM</sub>) of SO<sub>2</sub> on Io is poorly known but has a significant effect on the band depths for a given SO<sub>2</sub> column abundance (N<sub>SO2</sub>). Observations of Io at different wavelengths yield different values for T<sub>ATM</sub>. Mid-infrared observations at 19 μm tend to produce “cold” atmospheric temperatures (<150 K) [Spencer et al., 2005; Tsang et al., 2012], while recent measurements at 4 μm showed higher gas temperatures (170 ± 20 K) [Lellouch et al., 2015], and this discrepancy remains to be resolved. To estimate T<sub>ATM</sub> before eclipse ingress, we summed all spectra prior to eclipse ingress from both days (Figures 1 and 2) to create a high-SNR (674 on the continuum and 37 on the depth of the 530.42 cm<sup>-1</sup> band) spectrum (Figure 4) and fitted for both (N<sub>SO2</sub>) and (T<sub>ATM</sub>) using our radiative transfer model. Figure 4 also shows the other numerous SO<sub>2</sub> bands in our spectrum and our ability to fit all bands for N<sub>SO2</sub> and T<sub>ATM</sub>. The best fit retrieved N<sub>SO2</sub> and T<sub>ATM</sub> was 2.27 ± (0.3) × 10<sup>16</sup> cm<sup>-2</sup> and 115 (–15, +35) K, respectively. The fitting was done with a downhill simplex method for multidimensional chi-square minimization. This low temperature is consistent with previous determinations of T<sub>ATM</sub> at these wavelengths. We also chose to model an upper limit of T<sub>ATM</sub> = 170 K as derived at 4 μm data because not only is it a recent and strong constraint on the gas temperature on Io but also it is consistent with the radiative-convective model of a hydrostatic atmosphere in equilibrium with solar

**4.1. Derivation of T<sub>SURF</sub>**

The width of the TEXES slit at Gemini on Io was 0.75 arcsec, less than Io’s 1.1 arc sec diameter. Therefore, Io overfills the slit, and some light loss is expected. The amount of loss depends on guiding and seeing variations. However, the fact that flux varies by less than 2.5% in the 41 min prior to eclipse on 24 November, and the consistency of the absolute fluxes and their variations after eclipse ingress on the two nights (Figure 3), suggests that these variations were modest (with the exception of the last two points on 24 November). We thus have confidence in the relative changes in thermal flux in Figure 3. The last two measurements on 24 November, spanning the last 15 mins, have been omitted due to a loss in guiding on Io. We use the most time appropriate fluxes from 17 November in lieu of these data that span the same time in eclipse.

Note that the TEXES data are not absolutely calibrated in flux. To obtain absolute T<sub>SURF</sub> in Kelvins, we took previously

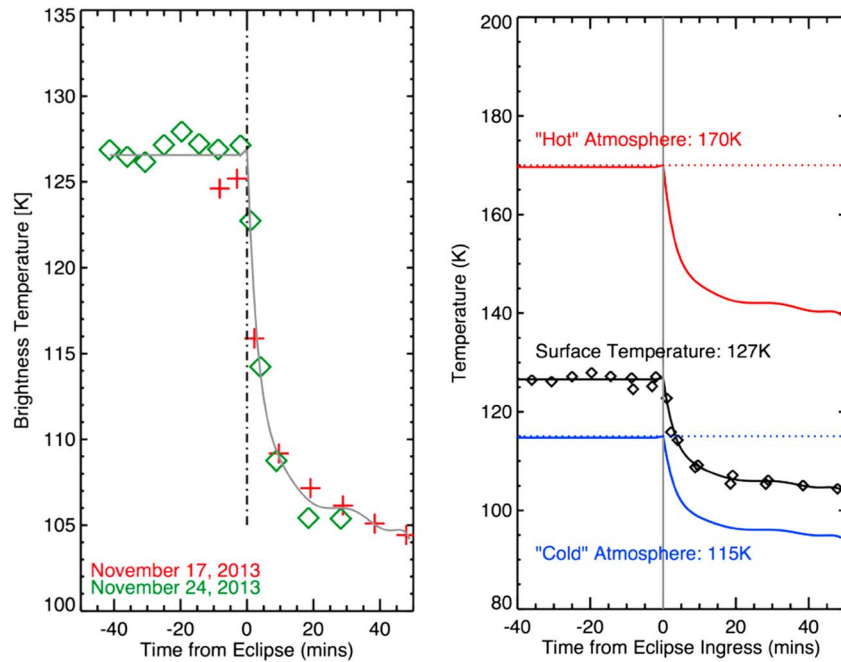


**Figure 4.** The coadded Gemini-TEXES spectrum from all observations before Jupiter eclipse. All observations from 17 to 23 November 2013 prior to the eclipse ingress were coadded to create this high signal to noise (SNR) (674 on the continuum, 37 on the  $530.42\text{ cm}^{-1}$  line) spectrum (black). This spectrum was fitted with a model (red) [Spencer *et al.*, 2005], residuals given in blue, to derive the pre-eclipse  $T_{\text{ATM}}$ .

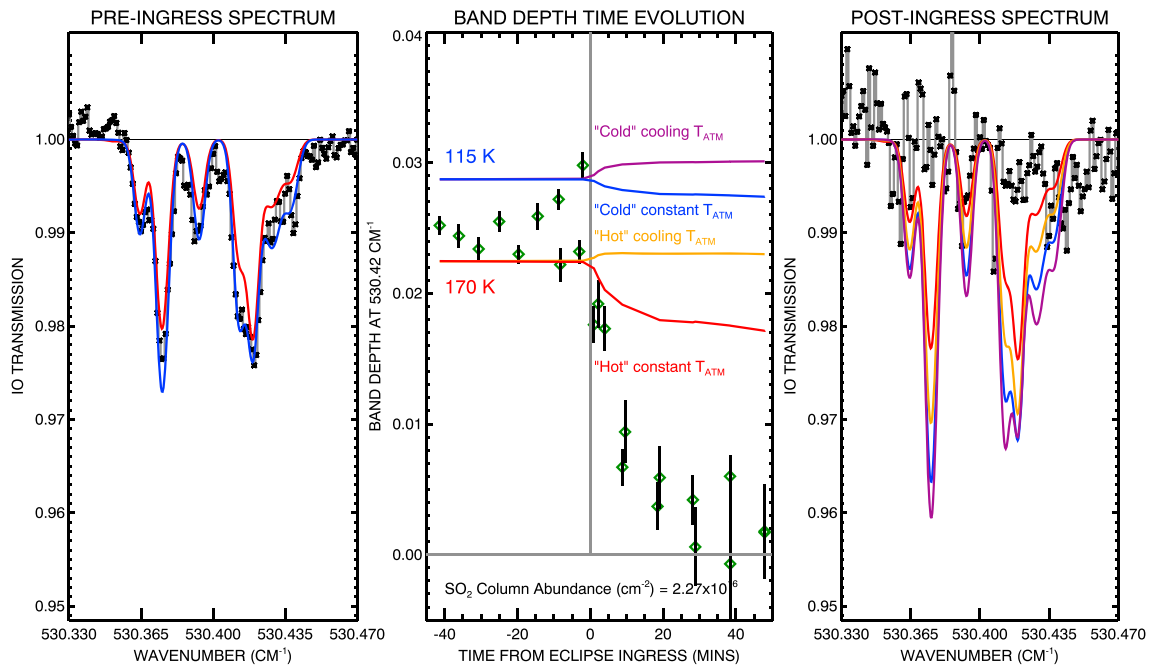
heating at these low densities (approximately few nanobars) in the first scale height of Io's atmosphere ( $\sim 10\text{ km}$ ) which these observations probe [Sinton and Kaminski, 1988; Lellouch *et al.*, 2015]. With these two initial pre-ingress values of  $T_{\text{ATM}}$ , we then modeled two end-member scenarios (Figure 5) in which (1)  $T_{\text{ATM}} = \text{constant}$  and (2)  $T_{\text{ATM}}/T_{\text{SURF}}$  is constant.  $T_{\text{SURF}}$  is derived from the post-eclipse ingress cooling profile by fitting a polynomial function to the values of  $T_{\text{SURF}}$  inferred above.

### 5. Results: The Interpretation

For simplicity, we approximate Io as a uniform disk with constant temperature and obtain  $T_{\text{SURF}}$  from the decrease in the observed  $19\text{ }\mu\text{m}$  continuum thermal flux, which was taken at the same time as the  $\text{SO}_2$  bands.  $T_{\text{SURF}}$  was obtained throughout the eclipse period, is a direct measure of surface cooling, and is consistent with previous observations at similar wavelengths [Sinton and Kaminski, 1988]. The decrease in  $19\text{ }\mu\text{m}$  flux ( $T_{\text{B}}$ ) is in good agreement on the two dates, indicating that the guiding on Io throughout the eclipse period was accurate and consistent between the dates and changes in observed flux are a good measure of disk-integrated flux changes. This equates to  $T_{\text{SURF}}$  varying from  $127\text{ K}$  out of eclipse [Sinton and Kaminski, 1988], cooling to  $105\text{ K}$  in eclipse. The pre-eclipse  $T_{\text{ATM}}$  was measured using a spectrum that was summed from all the pre-eclipse spectra to increase SNR as previously described. The temperature sensitive wing of the main  $530.42\text{ cm}^{-1}$   $\text{SO}_2$  line [Tsang *et al.*, 2012], revealed  $T_{\text{ATM}}$  to be  $115 (+35, -15)\text{ K}$ , with a best fit  $\text{SO}_2$  column density of  $N_{\text{SO}_2} = 2.27 \times 10^{16}\text{ cm}^{-2}$ . Because an individual spectrum in eclipse did not have sufficient SNR to measure  $T_{\text{ATM}}$ , we modeled the evolution of  $T_{\text{ATM}}$  through the eclipse period with two end-member assumptions: either a cooling atmosphere with  $T_{\text{ATM}}$  in fixed ratio to  $T_{\text{SURF}}$ , or  $T_{\text{ATM}}$  constant throughout the eclipse period. Since no observations of  $T_{\text{ATM}}$  exist, these end-member profiles of  $T_{\text{ATM}}$  provide good

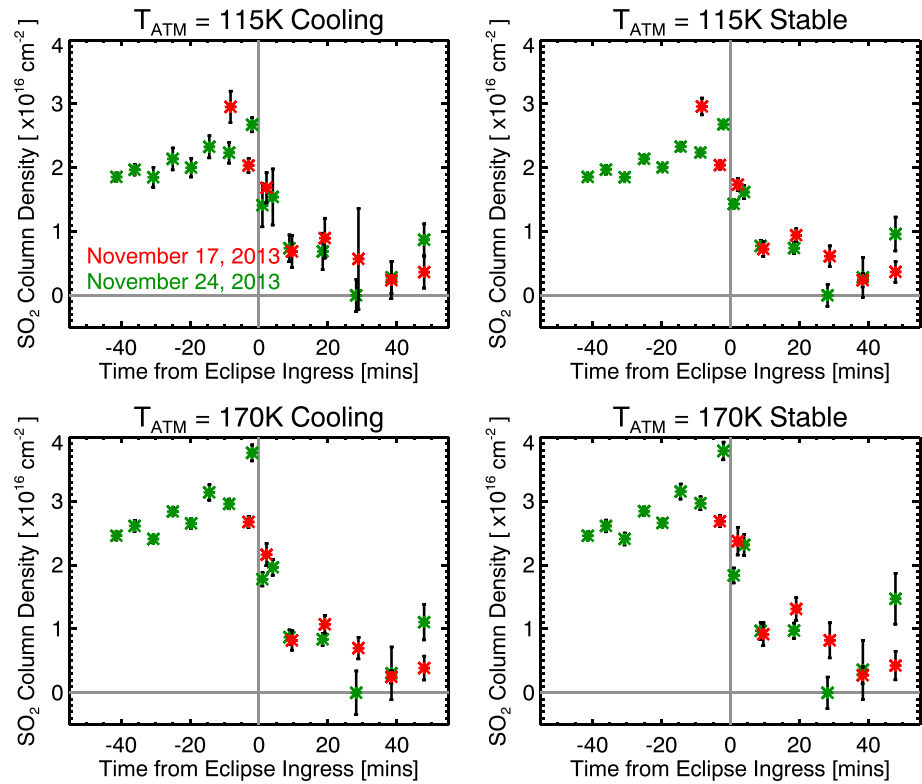


**Figure 5.** The inferred brightness temperature ( $T_B$ ) of Io during the observations. The observations in the  $19\ \mu\text{m}$  flux are converted to  $T_B$ , and a least squares fit is fitted to obtain the time dependent evolution of  $T_{\text{SURF}}(t)$  (right). The assumed surface temperatures ( $T_{\text{SURF}}$ ) and atmospheric temperatures ( $T_{\text{ATM}}$ ) modeled for the eclipse events.



**Figure 6.** The collapse of Io's atmosphere. Four idealized constant density (static) atmospheres are modeled, with differing starting atmospheric temperatures ( $T_{\text{ATM}}$ ) and assumed temperature behavior in eclipse. The evolution of  $T_{\text{SURF}}$  is constrained by the observed decay of the  $19\ \mu\text{m}$  fluxes (Figure 3). (middle) The  $530.42\ \text{cm}^{-1}$  band depth for both days has been plotted. Once eclipse occurs, for initial  $T_K = 115\ \text{K}$  (blue) and  $170\ \text{K}$  (red), the atmosphere either cools in fixed proportion to the surface temperature ( $T_{\text{SURF}}$ ) or remains constant, resulting in the band depths presented. (left and right) The average of the first and last 15 min of spectra in Figure 6 (middle), compared with synthetic spectra generated at various  $T_{\text{ATM}}$  with fixed  $\text{SO}_2$  density. These spectra represent end-member behaviors possible on Io for a noncollapsing atmosphere. The observed drop in band depth in eclipse cannot be matched with a constant atmospheric density in any of these models, showing atmospheric collapse has occurred.





**Figure 7.** Io’s collapsing SO<sub>2</sub> atmosphere during Jupiter eclipse. Inferred atmospheric density before and after eclipse ingress for the four atmospheric temperature models in Figure 3. For all temperature models and both observed eclipses, the best fit SO<sub>2</sub> column abundance ( $N_{\text{SO}_2}$ ,  $\text{cm}^{-2}$ ) shows the primary molecular SO<sub>2</sub> atmosphere of Io collapsing during the 40 min following Jupiter eclipse ingress.

boundary conditions to explore the sensitivity of the derived evolution of Io’s atmospheric density in eclipse to assumptions about  $T_{\text{ATM}}$ .

Figure 6 shows the observed  $530.420\text{ cm}^{-1}$  band depths (black green) with time, compared to modeled  $530.420\text{ cm}^{-1}$  band depths with the above assumptions. We assume a noncollapsing atmosphere with  $N_{\text{SO}_2} = 2.27 \times 10^{16}\text{ cm}^{-2}$ , an assumed initial atmospheric temperature  $T_{\text{ATM}} = 115\text{ K}$ , which is the best fit  $T_{\text{ATM}}$  from our data and  $T_{\text{ATM}} = 170\text{ K}$  which corresponds to the best estimated temperature from *Lellouch et al.* [2015] derived at  $4\text{ }\mu\text{m}$ . The constant or cooling atmosphere assumptions are described above, and we use  $T_{\text{SURF}}$  derived from our disk-integrated Gemini  $19\text{ }\mu\text{m}$  fluxes. For both model atmospheres where  $T_{\text{ATM}}$  is cooling at the same rate as the cooling of  $T_{\text{SURF}}$ , the  $530.420\text{ cm}^{-1}$  band depth post-ingress remains largely unchanged relative to their pre-ingress levels. This is due to a balance between  $T_{\text{SURF}}$  cooling in the absence of sunlight, which reduces the surface contrast illuminating the overlying atmosphere and produces a decrease in band depth, and  $T_{\text{ATM}}$  cooling at the same time, which increases the band depths in these low- $N_{\text{SO}_2}$  non-LTE regimes. For the cases where  $T_{\text{ATM}} = \text{constant}$ ,  $T_{\text{SURF}}$  produces a decrease in band depth as Io cools off in eclipse, but the decrease in both cases is much less than the observed decrease in the  $N_{\text{SO}_2}$  band depths. The observed dramatic drop in band strength thus indicates  $N_{\text{SO}_2}$  must be decreasing in eclipse. We can also derive SO<sub>2</sub> column density given our four assumptions about  $T_{\text{ATM}}$ . Figure 7 shows the best fit derived  $N_{\text{SO}_2}$  and their errors, assuming the four  $T_{\text{ATM}}$  evolutions defined already. The tabulation of these values can be found in Table 2.

### 6. Discussion

These observations provide the first direct evidence that Io’s primary molecular SO<sub>2</sub> atmosphere collapses in eclipse, with SO<sub>2</sub> condensing on the surface as SO<sub>2</sub> frost. Our observations also allow us to constrain the

**Table 2.** The Derived SO<sub>2</sub> Column Densities as a Function of Time From Eclipse Ingress, Assuming  $T_{\text{ATM}} = 115 \text{ K}$  or  $170 \text{ K}$ , Both Either Held Stable and Cooling, Which Is Plotted as Figure 7

Time Relative to Jupiter Eclipse Ingress (min)	SO <sub>2</sub> Column Density ( $1 \times 10^{16} \text{ cm}^{-2}$ )			
	$T_{\text{ATM}} = 115 \text{ K}$ Cooling	$T_{\text{ATM}} = 115 \text{ K}$ Stable	$T_{\text{ATM}} = 170 \text{ K}$ Cooling	$T_{\text{ATM}} = 170 \text{ K}$ Stable
-41.33	1.85 ± 0.07	1.85 ± 0.04	2.46 ± 0.07	2.46 ± 0.07
-36.05	1.97 ± 0.08	1.96 ± 0.06	2.61 ± 0.09	2.61 ± 0.09
-30.64	1.85 ± 0.16	1.84 ± 0.05	2.41 ± 0.06	2.41 ± 0.09
-25.00	2.14 ± 0.17	2.13 ± 0.05	2.84 ± 0.06	2.85 ± 0.07
-19.66	2.00 ± 0.15	2.00 ± 0.05	2.65 ± 0.08	2.66 ± 0.06
-14.41	2.33 ± 0.17	2.33 ± 0.06	3.14 ± 0.12	3.15 ± 0.12
-8.66	2.23 ± 0.16	2.24 ± 0.05	2.96 ± 0.08	2.97 ± 0.10
-8.24	2.95 ± 0.25	2.96 ± 0.13	4.33 ± 0.22	4.36 ± 0.19
-3.02	2.03 ± 0.11	2.04 ± 0.06	2.68 ± 0.09	2.69 ± 0.09
-2.00	2.67 ± 0.11	2.67 ± 0.05	3.76 ± 0.13	3.79 ± 0.14
1.00	1.41 ± 0.34	1.43 ± 0.06	1.78 ± 0.10	1.84 ± 0.12
2.17	1.69 ± 0.24	1.73 ± 0.09	2.16 ± 0.17	2.38 ± 0.22
4.00	1.54 ± 0.44	1.61 ± 0.10	1.96 ± 0.12	2.32 ± 0.16
8.81	0.74 ± 0.21	0.77 ± 0.08	0.87 ± 0.11	0.97 ± 0.13
9.57	0.69 ± 0.25	0.72 ± 0.11	0.82 ± 0.15	0.92 ± 0.18
18.48	0.69 ± 0.28	0.74 ± 0.08	0.84 ± 0.09	0.97 ± 0.12
19.09	0.90 ± 0.31	0.94 ± 0.10	1.07 ± 0.14	1.31 ± 0.18
28.19	0.00 ± 0.93	0.02 ± 0.17	0.00 ± 0.34	0.00 ± 0.25
28.84	0.57 ± 0.79	0.61 ± 0.16	0.70 ± 0.17	0.82 ± 0.27
38.39	0.24 ± 0.29	0.23 ± 0.10	0.25 ± 0.10	0.27 ± 0.13
38.43	0.28 ± 0.31	0.28 ± 0.30	0.30 ± 0.41	0.36 ± 0.46
47.88	0.87 ± 0.36	0.96 ± 0.26	1.11 ± 0.28	1.47 ± 0.40
47.89	0.36 ± 0.30	0.36 ± 0.17	0.39 ± 0.19	0.43 ± 0.22

spatial distribution of Io's atmosphere. The fact that these observations show SO<sub>2</sub> band depths decreasing until they almost disappear implies the atmosphere, at least on the hemisphere centered around 340° that is observed during eclipses, is global and not centered over volcanic hotspots; i.e., localized SO<sub>2</sub> over active volcanoes is a minor component of the atmosphere on this hemisphere. A single high value in SO<sub>2</sub> column density on 24 November just prior to eclipse gives the impression of a rise in column density before the collapse begins. This value is unlikely to be as high as indicated as the atmospheric density has no physical reason to increase prior to eclipse ingress.

In apparent contradiction to the conclusions of this study, recent mid-UV observations by the Hubble Space Telescope have suggested Io's atmosphere coming out of Jupiter eclipse does not rapidly respond to sunlight, as expected if the atmosphere was sublimation supported [Tsang *et al.*, 2015], as evidence by this work. One possible explanation of the difference could be longitudinal variations in atmospheric support. Multiwavelength observations [Spencer *et al.*, 2005; Feaga *et al.*, 2009; Tsang *et al.*, 2013] show the atmospheric density peaks at anti-Jupiter longitudes (~180°W) and decreases toward the sub-Jupiter hemisphere. The atmospheric densities at eclipse ingress longitudes (~340°W) are a factor of 2 lower than at eclipse egress longitudes (20°W) [Tsang *et al.*, 2012, 2013]. Egress longitudes also contain ~40% more volcanically active hotspots and paterae than at ingress longitudes as seen by the Galileo spacecraft [Feaga *et al.*, 2009; Hamilton *et al.*, 2013]. We postulate that at ingress longitudes, the atmosphere is dominated by ice sublimation, but at egress longitudes where the atmosphere is twice as thick, SO<sub>2</sub> emission from the larger number of volcanoes largely masks the sublimation response to sunlight. Further modeling and observations are needed to confirm both these observations and resolve this discrepancy.

Lastly, sulfur monoxide (SO), which has been detected on Io [de Pater *et al.*, 2002] is a noncondensable at Io temperatures. It has been suggested that SO might potentially inhibit any condensing SO<sub>2</sub> onto the surface by forming a thick diffusion layer [Moore *et al.*, 2009] between the surface and the SO<sub>2</sub> atmosphere, as the SO diffusion coefficient is inversely proportional to the SO<sub>2</sub> density. However, at the surface, SO recombines into S<sub>2</sub>O and SO<sub>2</sub>. Laboratory experiments that attempt to measure the vapor pressure expression of SO show that this fast reaction scheme prevents SO from remaining long enough to measure its vapor pressure

[Lellouch *et al.*, 1996]. Therefore, the SO “atmosphere” should collapse with the SO<sub>2</sub> atmosphere. The fact that we see the atmosphere collapse shows that any noncondensables such as SO do not affect the collapsing mechanism, as suggested by these laboratory measurements.

## 7. Conclusions

We used the Gemini North telescope to obtain data of Io’s molecular SO<sub>2</sub> atmosphere during Io’s eclipse ingress. Spectra were taken by the TEXES spectrometer at 530.42 cm<sup>-1</sup> (19 μm) on two separate ingress apparitions in 2013, at resolving powers of 67,000. The data and analysis show for the first time that the primary atmosphere of Io collapsed shortly after eclipse ingress. Our main conclusions are the following:

1. The main 530.420 cm<sup>-1</sup> SO<sub>2</sub> band depths was observed to decay away in the period of Jupiter eclipse, from 2.5 ± (0.08)% before the eclipse to 0.18 ± (0.16)% after 40 min in eclipse. It was also accompanied by a drop in 19 μm thermal flux, equating to a drop in the brightness temperature from 127 K to 105 K.
2. Modeling shows that for end-member atmospheric temperatures of 115 K and 170 K that are most likely found on Io, the SO<sub>2</sub> band depths cannot be reconciled with an atmosphere that is static in time and which does not respond to sunlight.
3. The atmospheric density drop according to the vapor pressure laws imply a decrease from 2.0–2.5 × 10<sup>16</sup> cm<sup>-2</sup> to ~0.5 × 10<sup>16</sup> cm<sup>-2</sup> to match the observed drop in band depths. The atmosphere collapses by a factor of 5 ± 2.
4. Combined with the HST-COS egress UV observations taken a few years prior, we can infer that the atmosphere at ingress longitudes are mostly sublimation driven, while at egress longitudes, the atmosphere is mostly volcanically dominated. This agrees with the distribution of atmospheric density with longitudes, as well as the distribution of volcanic centers found on Io. The data also show that the effect of any non-condensable gases is negligible.

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## References

- Clarke, J. T., J. Ajello, J. Luhmann, N. Schneider, and I. Kanik (1994), Hubble Space Telescope UV spectral observations of Io passing into eclipse, *J. Geophys. Res.*, *99*(E4), 8387–8402.
- de Pater, I., H. Roe, J. R. Graham, D. F. Strobel, and P. Bernath (2002), Detection of the forbidden SO rovibronic transition on Io at 1.7 mm, *Icarus*, *156*, 296–301.
- Feaga, L. M., M. McGrath, and P. D. Feldman (2009), Io’s dayside SO<sub>2</sub> atmosphere, *Icarus*, *201*, 570–584.
- Feldman, P. D., D. F. Strobel, H. W. Moos, K. D. Retherford, B. C. Wolven, M. A. McGrath, F. L. Roesler, R. C. Woodward, R. J. Oliverson, and G. E. Ballester (2000), Lyman-alpha imaging of the SO<sub>2</sub> distribution on Io, *Geophys. Res. Lett.*, *27*, 1787–1789, doi:10.1029/1999GL011067.
- Flaud, J.-M., A. Perrin, L. M. Salah, W. J. Lafferty, and G. Guelachvili (1993), A reanalysis of the (010), (020), (100), and (001) rotational levels of 32S16O<sub>2</sub>, *J. Mol. Spectrosc.*, *160*, 272–278.
- Hamilton, C. W., C. D. Beggan, S. Still, M. Beuthe, R. M. C. Lopes, D. A. Williams, J. Radebaugh, and W. Wright (2013), Spatial distribution of volcanoes on Io: Implications for tidal heating and magma ascent, *Earth Planet. Sci. Lett.*, *361*, 272–286.
- Jessup, K.-L., and J. R. Spencer (2015), Spatially resolved HST/STIS observations of Io’s dayside equatorial atmosphere, *Icarus*, *248*, 165–189, doi:10.1016/j.icarus.2014.10.020.
- Jessup, K. L., J. R. Spencer, G. E. Ballester, R. R. Howell, F. Roesler, M. Vigil, and R. Yelle (2004), The atmospheric signature of Io’s Prometheus plume and anti-Jovian hemisphere: Evidence for a sublimation atmosphere, *Icarus*, *169*, 197–215.
- Lacy, J. H., M. J. Richter, T. K. Greathouse, D. T. Jaffe, and Q. Zhu (2002), TEXES: A sensitive high-resolution grating spectrograph for the mid-infrared, *Pub. Astro. Soc. Pacific*, *114*, 153–168.
- Lellouch, E. (1996), Io’s Atmosphere, *Not Yet Understood*, *124*, 1–21.
- Lellouch, E., M. J. S. Belton, I. DePater, G. Paubert, S. Gulkis, and T. Encrenaz (1992), The structure, stability, and global distribution of Io’s atmosphere, *Icarus*, *98*, 271–295.
- Lellouch, E., D. F. Strobel, M. J. S. Belton, M. E. Summers, G. Paubert, and R. Moreno (1996), Detection of sulfur monoxide in Io’s atmosphere, *Astrophys. J.*, *459*, L107–L110.
- Lellouch, E., M. A. McGrath, and K. L. Jessup (2007), Io’s atmosphere, in *Io After Galileo*, edited by R. M. C. Lopes and J. R. Spencer, pp. 231–264, Springer, Praxis.
- Lellouch, E., M. Ali-Dib, K.-L. Jessup, A. Smette, H.-U. Käufel, and F. Marchis (2015), Detection and characterization of Io’s atmosphere from high-resolution 4-μm spectroscopy, *Icarus*, *253*, 99–114, doi:10.1016/j.icarus.2015.02.018.
- López-Puertas, M., and F. W. Taylor (2001), *Non-LTE Radiative Transfer in the Atmosphere*, World Sci., Singapore.
- López-Valverde, M. A., and M. López-Puertas (1994), A non-local thermodynamic equilibrium radiative transfer model for infrared emissions in the atmosphere of Mars: 1. Theoretical basis and nighttime populations of vibrational levels, *J. Geophys. Res.*, *99*, 13,093–13,116, doi:10.1029/94JE00635.
- Moore, C. H., D. B. Goldstein, P. L. Varghese, L. M. Trafton, and B. Stewart (2009), 1-D DSMC simulation of Io’s atmospheric collapse and reformation during and after eclipse, *Icarus*, *201*, 585–597.
- Moulet, A., M. A. Gurwell, E. Lellouch, and R. Moreno (2010), Simultaneous mapping SO<sub>2</sub>, SO, NaCl in Io’s atmosphere with the submillimeter array, *Icarus*, *208*, 353–365.
- Pearl, J., R. Hanel, V. Kunde, W. Maguire, K. Fox, S. Gupta, C. Ponnampuruma, and F. Raulin (1979), Identification of gaseous SO<sub>2</sub> and new upper limits for other gases on Io, *Nature*, *280*, 755–758.

- Retherford, K., et al. (2007), Io's atmospheric response to eclipse: UV aurorae observations, *Science*, *318*, 237–240.
- Roth, L., J. Saur, K. D. Retherford, D. F. Strobel, and J. R. Spencer (2011), Simulation of Io's auroral emission: Constraints on the atmosphere in eclipse, *Icarus*, *214*, 495–509.
- Saur, J., and D. F. Strobel (2004), Relative contributions of sublimation and volcanos to Io's atmosphere inferred from its plasma interaction during solar eclipse, *Icarus*, *171*, 411–420.
- Sinton, W., and C. Kaminski (1988), Infrared observations of eclipses of Io, its thermophysical parameters and the thermal radiation of the Loki Volcano and Environs, *Icarus*, *75*, 207–232.
- Summer, M. E., and D. F. Strobel (1996), Photochemistry and vertical transport in Io's atmosphere and ionosphere, *Icarus*, *120*, 290–316.
- Spencer, J. R., E. Lellouch, M. J. Richter, M. A. López-Valverde, K. L. Jessup, T. K. Greathouse, and J. M. Flaud (2005), Mid-infrared detection of large longitudinal asymmetries in Io's SO<sub>2</sub> atmosphere, *Icarus*, *176*, 283–304.
- Strobel, D. F., X. Zhu, and M. E. Summers (1994), On the vertical thermal structure of Io's atmosphere, *Icarus*, *111*, 18–30.
- Tsang, C. C. C., J. R. Spencer, E. Lellouch, M. A. Lopez-Valverde, M. J. Richter, and T. K. Greathouse (2012), Io's atmosphere: Constraints on sublimation support from density variations on seasonal timescales using NASA IRTF/TEXES observations from 2001 to 2010, *Icarus*, *217*, 277–296.
- Tsang, C. C. C., J. R. Spencer, and K. L. Jessup (2013), Synergistic observations of Io's atmosphere in 2010 from HST-COS in the mid-ultraviolet and IRTF-TEXES in the mid-infrared, *Icarus*, *226*, 604–616.
- Tsang, C. C. C., J. R. Spencer, and K.-L. Jessup (2015), Non-detection of post-eclipse changes in Io's Jupiter-facing atmosphere: Evidence for volcanic support?, *Icarus*, *248*, 243–253, doi:10.1016/j.icarus.2014.10.033.
- Wolven, B. C., H. W. Moos, K. D. Retherford, P. D. Feldman, D. F. Strobel, W. H. Smyth, and F. L. Roesler (2001), Emission profile of neutral oxygen and sulfur in Io's exospheric corona, *J. Geophys. Res.*, *106*(A11), 26,155–26,182.