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Icarus 176 (2005) 283–304
ICARUS
www.elsevier.com/locate/icarus

Mid-infrared detection of large longitudinal asymmetries in Io's SO_2 atmosphere

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Received 26 July 2004; revised 13 January 2005

Available online 19 April 2005

Abstract

We have observed about 16 absorption lines of the ν_2 SO_2 vibrational band on Io, in disk-integrated 19-µm spectra taken with the TEXES high spectral resolution mid-infrared spectrograph at the NASA Infrared Telescope Facility in November 2001, December 2002, and January 2004. These are the first ground-based infrared observations of Io's sunlit atmosphere, and provide a new window on the atmosphere that allows better longitudinal and temporal monitoring than previous techniques. Dramatic variations in band strength with longitude are seen that are stable over at least a 2 year period. The depth of the strongest feature, a blend of lines centered at 530.42 cm^{-1}, varies from about 7% near longitude 180° to about 1% near longitude 315° W, as measured at a spectral resolution of 57,000. Interpretation of the spectra requires modeling of surface temperatures and atmospheric density across Io's disk, and the variation in non-LTE ν_2 vibrational temperature with altitude, and depends on the assumed atmospheric and surface temperature structure. About half of Io's 19-µm radiation comes from the Sun-heated surface, and half from volcanic hot spots with temperatures primarily between 150 and 200 K, which occupy about 8% of the surface. The observations are thus weighted towards the atmosphere over these low-temperature hot spots. If we assume that the atmosphere over the hot spots is representative of the atmosphere elsewhere, and that the atmospheric density is a function of latitude, the most plausible interpretation of the data is that the equatorial atmospheric column density varies from about 1.5×10^{17} cm^{-2} near longitude 180° W to about 1.5×10^{16} cm^{-2} near longitude 300° W, roughly consistent with HST UV spectroscopy and Lyman-α imaging. The inferred atmospheric kinetic temperature is less than about 150 K, at least on the anti-Jupiter hemisphere where the bands are strongest, somewhat colder than inferred from HST UV spectroscopy and millimeter-wavelength spectroscopy. This longitudinal variability in atmospheric density correlates with the longitudinal variability in the abundance of optically thick, near-UV bright SO_2 frost. However it is not clear whether the correlation results from volcanic control (regions of large frost abundance result from greater condensation of atmospheric gases supported by more vigorous volcanic activity in these regions) or sublimation control (regions of large frost abundance produce a more extensive atmosphere due to more extensive sublimation). Comparison of data taken in 2001, 2002, and 2004 shows that with the possible exception of longitudes near 180° W between 2001 and 2002, Io's atmospheric density does not appear to decrease as Io recedes from the Sun, as would be expected if the atmosphere were supported by the sublimation of surface frost, suggesting that the atmosphere is dominantly supported by direct volcanic supply rather than by frost sublimation. However, other evidence such as the smooth variation in atmospheric abundance with latitude, and atmospheric changes during eclipse, suggest that sublimation support is more important than volcanic support, leaving the question of the dominant atmospheric support mechanism still unresolved.

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doi:10.1016/j.icarus.2005.01.019

Keywords: Io; Atmospheres, Structure; Infrared observations; Radiative transfer; Spectroscopy

1. Introduction

Io's atmosphere is one of the most unusual and interesting in the Solar System, due to its unique composition (dominantly SO_2) and unique structure. There are large lateral variations in density which are thought to result from rapid condensation of the dominant SO_2 gas away from volcanic or sublimation sources. The atmosphere thus offers unique insights into basic atmospheric physics. It is also the medium through which Io supplies the mass of the complex plasma that fills the jovian magnetosphere, and thus must be understood if we are to understand the jovian magnetospheric plasma. Recent reviews on Io's atmosphere and its interaction with the plasma torus can be found in McGrath et al. (2004) and Saur et al. (2004).

The atmosphere appears to cover most of the surface at low latitudes but is much thinner at high latitudes, as revealed most directly by imaging in reflected Lyman-α by the Hubble Space Telescope (HST). A subsolar SO_2 column density of a few $\times 10^{16}$ cm^{-2} has been inferred from the Lyman-α images (Feldman et al., 2000; Feaga et al., 2004). HST disk-integrated observations of 0.20–0.23 μm SO_2 gas absorption bands give subsolar densities of a few $\times 10^{16}$ cm^{-2} (Ballester et al., 1994; Jessup et al., 2002) to $\sim 10^{17}$ cm^{-2} (Trafton et al., 1996) if the atmosphere is assumed to be concentrated over a few tens of percent of the surface at low latitudes, as suggested by the Lyman-α images. Disk-resolved 0.20–0.23 μm spectroscopy away from plume sources gives low-latitude SO_2 densities of 1.5×10^{16} cm^{-2} at longitude 318° W (McGrath et al., 2000) and 1.3×10^{17} cm^{-2} at 160° W (Jessup et al., 2004). High column densities up to 10^{19} cm^{-2} have been inferred from Galileo UVS data (Hendrix et al., 1999), but are dependent on assumptions about the surface albedo, as UVS did not resolve individual SO_2 gaseous absorption bands.

SO_2 column density appears to be modestly enhanced over at least some volcanos. Voyager IRIS observations of the ν_3 vibrational band at 7.4 μm implied 9×10^{16} cm^{-2}–2×10^{18} cm^{-2} of SO_2 at Loki (Pearl et al., 1979; reinterpreted by Lellouch et al., 1992), and UV absorption over Pele implied an SO_2 abundance of 3×10^{16} cm^{-2} (McGrath et al., 2000) and 7×10^{16} cm^{-2} (Spencer et al., 2000a), while abundance over Prometheus reached 1.8×10^{17} cm^{-2} (Jessup et al., 2004). Disk-integrated mm-wave observations of SO_2 emission lines require local concentrations of a few $\times 10^{17}$ cm^{-2} of SO_2 at temperatures >600 K to match observed line widths, if the atmosphere is static (Lellouch et al., 1992): such high temperatures are difficult to explain (Strobel et al., 1994). Lower temperatures, and local abundances of about 1×10^{17} cm^{-2}, more consistent with the UV results, are possible if mm line widths are due to rapid motions associated with plumes or supersonic winds (Ballester et al., 1994; Lellouch, 1996). In addition to SO_2, lesser amounts of SO (Lellouch et al., 1996; McGrath et al., 2000), NaCl (Lellouch et al., 2003) and S_2 (Spencer et al., 2000a) have also been detected, as have neutral atomic emissions from S, O, and Na (Ballester et al., 1987; Geissler et al., 1999a, 2001a, 2004; Wolven et al., 2001; Feaga et al., 2004; Roesler et al., 1999; Bouchez et al., 2000), and molecular emissions from SO (dePater et al., 2002) and, probably, SO_2 and/or S_2 (Geissler et al., 1999a, 2001a, 2004; Jessup et al., 2004). The emission data are more difficult to interpret in terms of bulk atmospheric properties than the absorption data, as emission strength depends on excitation and dissociation mechanisms as well as atomic or molecular abundances.

SO_2 gas appears to be released by the volcanos either from primary vents (Spencer et al., 2000a) or from interaction of lava with surface frosts (Milazzo et al., 2001), condensing on the surface to form the extensive deposits of SO_2 frost seen on Io (Douté et al., 2001). The atmosphere is supported by a combination of direct volcanic supply and frost sublimation (Fanale et al., 1982; Ingersoll, 1989; Moreno et al., 1991; Wong and Smyth, 2000; Zhang et al., 2003). The relative roles of the volcanos and the surface frost in directly supporting the atmosphere depend on the frost temperature and the volcanic supply rate, and have not yet been determined. The arguments for the dominance of one or the other mechanism are considered later, in the discussion section. The question is important because a sublimation-supported atmosphere is likely to collapse at night and during Jupiter eclipse due to frost cooling, dramatically changing the interaction of Io with the magnetosphere (Wong and Smyth, 2000), and will have a different local distribution, being concentrated more around SO_2 frost deposits than active volcanic plumes.

Studies have been hampered by the difficulty in observing Io's atmosphere. While the first SO_2 detection (Pearl et al., 1979) was at 7.4 μm, all subsequent observations of the sunlit molecular atmosphere (till now) have been in the Lyman-α and 0.2–0.3-μm regions of the ultraviolet, where the HST is required, or at mm wavelengths, requiring large telescopes such as IRAM and CSO that have little time available for planetary studies. 1.7-μm molecular SO emission is visible from the ground during Jupiter eclipse, perhaps due to direct volcanic emission of excited SO (dePater et al., 2002), but is difficult to relate to the bulk atmosphere. Full characterization of the atmosphere's temporal and spatial variability has thus been difficult.

Here we describe and interpret the first ground-based detection of Io's sunlit SO_2 atmosphere in the infrared. These observations open a new window for the study of Io's unique