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DETECTION OF SULFUR MONOXIDE IN IO'S ATMOSPHERE

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ABSTRACT

Millimeter-wave observations of Io with the IRAM 30 m telescope have allowed the detection of two rotational lines of SO at 219.949 and 138.178 GHz in Io's atmosphere. The observations can be fitted by assuming that gaseous SO is collocated with SO_2 on a restricted fraction of Io's surface. In this case, the SO/SO_2 mixing ratio is 3%–10%, in agreement with predictions from one-dimensional photochemical models and suggesting a vertical eddy diffusion coefficient in the range 3×10^7 to 3×10^8 cm^2 s^{-1}. Alternatively, SO could constitute a tenuous, global atmosphere with column density in the range $(2–6) \times 10^{14}$ cm^{-2}. Photochemistry in SO_2 hydrostatic and/or volcanic plume atmospheres and horizontal transport can conceivably produce such an extended SO atmosphere.
Subject headings: planets and satellites: individual (Io) — radio lines: solar system

1. INTRODUCTION

Sulfur monoxide (SO) has long been suspected to be a significant constituent of Io's atmosphere, as the main product of the SO_2 photolysis, initiated by (Kumar 1980, 1982, 1985; Summers 1985; Summers & Strobel 1996)

$$SO_2 + h\nu \rightarrow SO + O \quad (\lambda \leq 2190 \text{ Å}). \qquad (1)$$

SO is lost chemically by reaction with itself (SO + SO → SO_2 + S) and by photolysis, but removal by transport is the main loss. Most one-dimensional photochemical models have predicted that SO could constitute up to ~10% of the SO_2 abundance. For this reason, shortly after our detection of SO_2 in Io's atmosphere at millimeter wavelengths (Lellouch et al. 1990, 1992), we have initiated a search for SO with the Institut de Radio-Astronomie Millimétrique (IRAM) 30 m telescope at Pico Veleta, Spain.

2. OBSERVATIONS

Observations at IRAM were made using two heterodyne receivers operating in single-sideband mode at 1.3 and 2 mm. Standard pointing and calibration techniques were employed, with Jupiter being used as the pointing source. Observations were performed in a fast version of position switch mode (wobbling at 0.25 Hz), except on 1995 June 24, when a frequency switch mode was used. For more details about several particular aspects involved with the Io observations and their calibration, see Lellouch et al. (1992). All data presented here were calibrated in relative brightness temperature units scaled to Io's radius, i.e., they represent the brightness temperature contrast of Io's atmosphere with respect to the surface if the atmosphere entirely covers Io's disk. Preliminary searches for the SO(6–5) line at 219.949 GHz were conducted on 1990 November 28 (leading side of Io), 1993 January 4 (leading), and 1994 May 18 (trailing). In none of these observations was the SO line clearly present, but by averaging the three data sets, one could obtain a plausible detection (Lellouch et al. 1994). Io observations in 1995 May–June were therefore targeted specifically at this SO line, which was detected independently on four different observing nights (two on each side of Io; Fig. 1). In addition, on 1995 June 22–23, a reasonable detection of the weaker SO(4–3) line at 138.178 GHz was achieved (Fig. 2). For the 1995 June observations, frequency tuning and calibration were checked by observing the SO lines on the star RX Boo. Within the noise level, the lines observed on the leading and trailing side are similar (Fig. 1), and we hereafter focus on the analysis of the averaged lines. The strong SO_2 line at 143.057 GHz, detected during our previous Io runs (Lellouch et al. 1992, 1994), was reobserved on 1995 May 30–31 and June 24, providing a characterization of the SO_2 atmosphere at the time of our SO measurements. It is noteworthy that the SO_2 143 GHz line observed in 1995 was narrower than in previous years (line width estimated from a Gaussian fit: 0.27 ± 0.03 MHz vs. 0.41 ± 0.08 MHz in 1991 and 0.36 ± 0.05 MHz in 1994), suggesting possible long-term variability of Io's atmosphere (Lellouch 1995). Finally, it appears that the averaged SO(6–5) line (but not the SO_2 143 GHz line) is redshifted (by 95 ± 34 m s^{-1}) with respect to its rest frequency, as were some of the SO_2 lines observed in 1993 and 1994 (Lellouch et al. 1994). The study of the redshifts will be published elsewhere.

3. ANALYSIS

There is still considerable uncertainty on the pressure, horizontal distribution, and vertical structure of Io's atmosphere (e.g., Lellouch et al. 1992; Ballester et al. 1994; Trafton et al. 1996; Lellouch 1995). Analysis of SO_2 observations at millimeter and UV wavelengths has indicated that the SO_2 atmosphere is in the nbar range and probably patchy, covering 5%–40% of the projected surface. The vertical structure is one of the main unknowns. From comparison of SO_2 lines of different intensities, and assuming line thermal broadening in a hydrostatic equilibrium atmosphere, Lellouch et al. (1992) inferred a 600 K atmospheric temperature in the lowest scale heights. However, such a temperature cannot be accounted for by one-dimensional thermal models including solar, plasma ion, and Joule heating (Strobel, Zhu, & Summers 1994), suggesting an atmosphere associated with volcanic plumes rather than a background residual atmosphere in hydrostatic equilibrium (Ballester et al. 1994; Lellouch et al. 1994). Because of these uncertainties, our SO observations were

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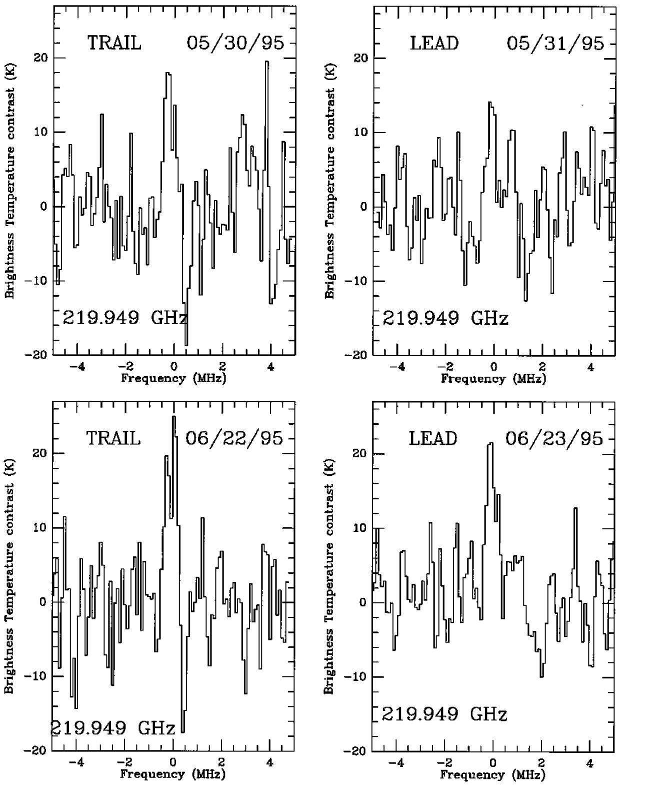

FIG. 1.—SO 219.949 GHz line observed on 1995 May 30 and 31, and June 22 and 23.

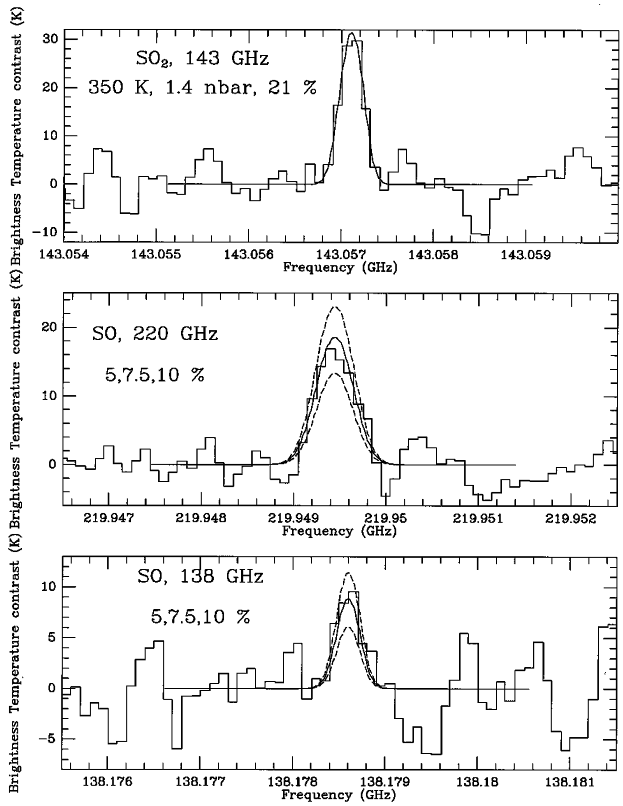

FIG. 2.—Fits of average SO_2 and SO lines with the localized hydrostatic models.

analyzed using three different radiative transfer models, meant to explore a range of possible conditions for Io's atmosphere. The first two models assume hydrostatic equilibrium for SO_2 and SO. In the first case, SO is assumed to be collocated with SO_2 at disk center (i.e., air mass = 1). The SO_2 line is used to define the SO_2 atmosphere characteristics. Because a single SO_2 line was observed in 1995, and because of the difficulties associated with the high temperatures, the atmospheric temperature T_{atm} is taken as a free parameter. Thus, for a suite of values of T_{atm}, the SO_2 line gives the SO_2 surface number density (pressure) and the fraction of the projected disk (ρ) covered by the atmosphere. Best-fit solutions are obtained for $p(SO_2) \sim 1$ nbar and $\rho = 20\%$. [Note, however, that because of its unusually narrow width, the SO_2 line can also be matched by a hemispheric atmosphere with bulk temperature $\gtrsim$250 K and column density of $(6 \pm 3) \times 10^{15}$ cm^{-2}, i.e., $p = 0.05$–0.15 nbar. Thus, the 1995 SO_2 spectrum does not allow one to conclude that the SO_2 atmosphere is patchy.] Then, using the same T_{atm} and ρ, the SO lines are fitted to obtain the SO surface pressure. SO/SO_2 mixing ratios in these "localized models" vary from 4% to 8% as a function of the assumed T_{atm} (Figure 3*a*). Figure 2 shows an example of a fit for $T_{atm} = 350$ K, $p(SO_2) = 1.4$ nbar, and $\rho = 21\%$, SO/SO_2 = 7.5%.

In a second case, the SO atmosphere is assumed to be horizontally uniform over Io's dayside. The SO lines are then solved for the SO column density as a function of the bulk atmospheric temperature. As shown in Figure 3*b*, column densities in the $(2$–$6) \times 10^{14}$ cm^{-2} range are found. These values indicate barely collisionally thick SO densities, for which the validity of hydrostatic equilibrium description becomes questionable if there are regions where SO is the only gas. Note that, if the SO_2 atmosphere is also hemispherically uniform, as tolerated by the 1995 SO_2 data, the SO/SO_2 mixing ratio is in the range 5%–10%, in agreement with the "localized" cases.

In a third model, the SO_2 and SO lines are assumed to originate directly from volcanic plumes. Simplified (ballistic) Monte Carlo plume models are generated (Lellouch et al. 1994), in which gas particles are launched from vents (assumed for simplicity at disk center) with a fixed velocity and a random direction inside a cone (a cone angle of 55° is adopted; Strom & Schneider 1982). Free parameters are (1) the ejection velocity v_e, (2) a number density scaling factor, giving the average column density within the plumes, and (3) the number of such plumes N_{pl}. A uniform and cold (but arbitrary) gas temperature of 250 K is assumed. This model is admittedly very crude in both its dynamical and thermal aspects, but it is probably adequate to first order to determine a SO/SO_2 mixing ratio within the plumes. The number density distribution as a function of radial distance, altitude, and vertical velocity is computed, and the radiative transfer equation is solved in vertical columns within the plume. The ejection velocity is determined from the line widths to be $\sim$0.5 km s^{-1}. The other two parameters can be determined independently if two SO_2 lines of different intensities are measured simultaneously (Lellouch et al. 1994). Here, however, the single 143 GHz SO_2 line can be fitted with any average column density $\langle SO_2 \rangle$ in the range 8×10^{15} to 3×10^{17} cm^{-2}; the corresponding N_{pl} is 50–200 (at larger column densities, the modeled line has too saturated a shape; at lower column densities, the total plume area exceeds Io's projected surface). While the ejection veloc-

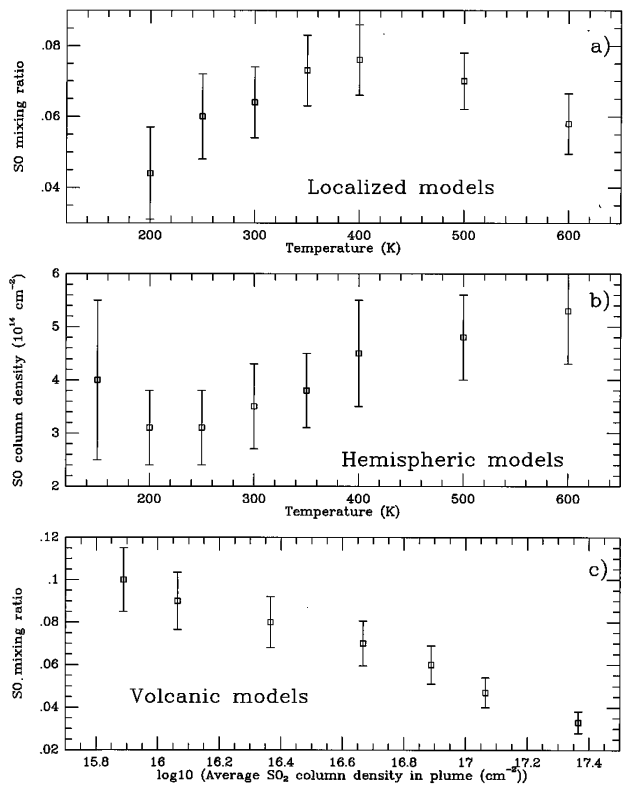

FIG. 3.—Domains of solutions for the three types of models (see text for details).

ity falls well within the range of velocities deduced from the *Voyager* plume observations, the number of required plumes is surprisingly large, as already noted (Lellouch et al. 1994; Johnson et al. 1995). For any ($\langle SO_2 \rangle$, N_{pl}) solution, the SO lines are then fitted assuming that SO and SO_2 are collocated in the plumes. SO/SO_2 mixing ratios inferred in this manner are found to be 3%–10% (Fig. 3*c*), indicating average SO column densities within the plumes in the range 7×10^{14} to 8×10^{15} cm^{-2}.

4. DISCUSSION

In Io's atmosphere, SO is chemically unreactive because its reactions with O_2 and itself have high activation energies of 4.8 and 3.5 kcal mole^{-1}, respectively, and most chemistry occurs near Io's surface, where the atmospheric temperature is low. Three-body recombination with O to recycle SO_2 is extremely slow at the nbar pressures on Io. Likewise, SO dimer formation is negligible. SO photolysis loss has an optically thin time constant of 5.6×10^4 s that is significantly longer than our inferred transport time constant of 10^4 s (see below). Thus, production of SO from SO_2 photolysis is balanced by transport either to the surface, where chemical interactions may transform it into S_2O and SO_2 (Schenk & Steudel 1965, 1968; Hapke & Graham 1989; Hapke 1989):

$$SO + SO + M \rightarrow (SO)_2, \quad (2)$$

$$(SO)_2 + SO \rightarrow S_2O + SO_2, \quad (3)$$

or to the exobase, where a variety of nonthermal escape processes can efficiently eject it into the Jovian magnetosphere.

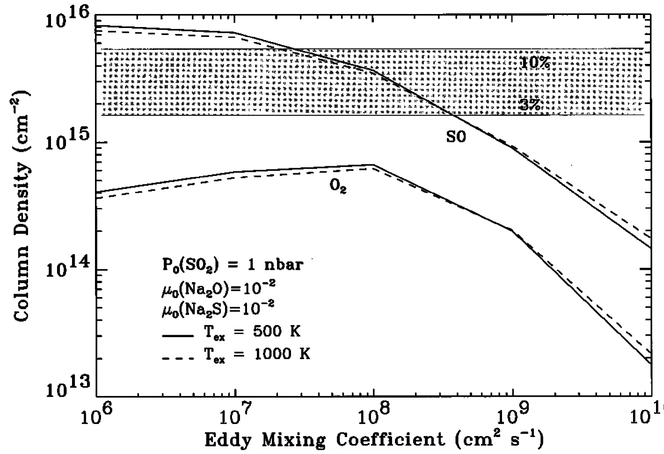

FIG. 4.—SO and O_2 column densities for the Summers & Strobel (1996) model as a function of eddy diffusion coefficient *K*. The SO_2 pressure is 1 nbar, the abundances of Na_2O and Na_2S are chosen as 1%, and two cases are presented corresponding to exospheric temperatures of 500 and 1000 K. The shaded area corresponds to the observed SO mixing ratio range.

When SO and SO_2 are collocated, both the "hydrostatic" and the "volcanic" models yield SO mixing ratios of 3%–10%. This compares well with photochemical model predictions (Kumar 1985; Summers 1985; Summers & Strobel 1996). Summers & Strobel (1996) imposed boundary conditions on SO that yield the maximum diffusive flux rates to both the surface [$\sim$(1–10) $\times 10^{11}$ cm^{-2} s^{-1}] and the exobase [$\sim$(1–5) $\times 10^{10}$ cm^{-2} s^{-1}] to simulate the rapid surface chemistry and efficient escape processes, and they investigated the SO and O_2 atmospheric mixing ratios as a function of the vertical eddy mixing coefficient *K*. Resupply from the surface was assumed to occur solely by an upward SO_2 flux and subsequent photolysis. Model results for our observationally inferred SO_2 surface pressure of 1 nbar are shown in Figure 4. The steady decline in the SO column density with increasing *K* is due to the increasing SO flux to the surface. The predicted SO mixing ratios and abundances are consistent with our inferred values when *K* is in the range (3–30) $\times 10^7$ cm^2 s^{-1}. Given the unique nature of Io's atmospheric dynamics, in which turbulence is likely generated by high Reynolds number flow driven by horizontal SO_2 pressure gradients, an independent estimate of *K* is very uncertain. If the surface is covered by SO_2 frost, Ingersoll (1989) shows that, on a local scale, each region of linear dimension $L = (2\pi)^{1/2}H/\alpha$ (*H* is the atmospheric scale height, and α is the sticking coefficient) controls its own pressure. Using the sonic speed as a characteristic flow velocity U_s, and a vertical scale for "overturning" of the gas $\sim H$, Summers & Strobel (1996) estimate $K \sim U_s(H/L)H \sim 10^9$ cm^2 s^{-1}. If SO is collocated with SO_2, then our inferred SO mixing ratio suggests that Io's atmosphere is less turbulent than this estimate.

Although current photochemical models are one-dimensional descriptions that assume a hydrostatic SO_2 atmosphere, there is increasing evidence that the atmosphere of Io is produced directly in volcanic plumes and transported away by horizontal winds. It must therefore be examined whether photochemistry in a volcanic plume may account for our observed SO column densities. A typical solution (Fig. 3*c*) corresponds to an average SO_2 column density of 5×10^{16} cm^{-2} in 80 volcanic plumes of $\sim$135 km radius (corresponding to $v_e = 0.5$ km s^{-1}), covering $\sim$22% of Io's surface. This gives

2×10^{33} SO_2 molecules on one hemisphere. With an effective SO_2 photodissociation rate of $J = 8 \times 10^{-6}\ s^{-1}$ for our inferred 1 nbar atmosphere, this gives an SO production rate of $\sim 1.6 \times 10^{28}\ s^{-1}$, which must be balanced by transport. Vertical eddy transport time is 6.4×10^3 s for $K = 10^8\ cm^2\ s^{-1}$. With a surface pressure of about 1 nbar, the molecular transport time is $\sim 10^5$ s at the surface and $\sim 10^3$ s at 100 km altitude. Horizontal transport can be taken as the time for travel over half an Io hemisphere at an average velocity 2 times the speed of sound (e.g., Ingersoll, Summers, & Schlipf 1985), i.e., $\sim 1.5 \times 10^4$ s. One can therefore adopt a transport time of 10^4 s. With these estimates, the SO column density is 8×10^{14} averaged over one hemisphere, or $4 \times 10^{15}\ cm^{-2}$ averaged over the plumes. These numbers are in satisfactory agreement with values derived for models 2 and 3, respectively, indicating that SO_2 photochemistry in volcanic plumes can plausibly account for the observed column densities.

The three different cases considered above must be viewed as illustrative cases of the possible distributions of the SO atmosphere on Io. None of them, however, is likely to be totally realistic given the complex and nonuniform distribution of volcanic and sublimation sources for the SO_2 atmosphere, and the existence of planet-wide supersonic flows away from the sources and toward the nightside (Ingersoll et al. 1985). Ingersoll & Lebeau (1993), in particular, proposed that, because SO (and other noncondensible products of the SO_2 photochemistry) cannot diffuse upstream, it may accumulate on the nightside and in the terminator regions. Our observations show that at least part of the SO atmosphere is on Io's dayside. Our inferred SO mixing ratios, when coupled with model results from Summers & Strobel (1996), imply that SO_2 photolysis is a sufficient atmospheric source of SO in the presence of rapid diffusive loss of SO and potent $SO \rightarrow SO_2$ surface conversion processes, and that the atmospheric lifetime of SO is short, $\leq 2 \times 10^4$ s. Testing our data against dynamically more realistic horizontal distributions of SO would certainly be very valuable.

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