

The Galilean Satellites as a Source of CO in the Jovian Upper Atmosphere¹

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Material from the Galilean satellites of Jupiter ejected by energetic particles in the Jovian magnetosphere may provide large sources of oxygen to the parent planet. Formation of a CO molecule is the ultimate fate of an oxygen atom in the upper Jovian atmosphere. This high altitude source of CO supports Beer and Taylor's (1978, *Astrophys. J.* 221) observations and analysis, provided that the globally averaged O atom input flux is $\sim 10^7$ cm⁻² sec⁻¹ and the eddy diffusion coefficient at the tropopause is $\sim 10^9$ cm² sec⁻¹. Implications for the possible presence of other atoms and molecules derived from the satellites are discussed.

1. INTRODUCTION

The composition of the visible Jovian atmosphere has long been regarded as representative of solar abundances. Reactive atoms such as C, N, and O are present in the form of saturated hydrides at approximately solar ratios. Condensable substances, e.g., H₂O and NH₃, are assumed to form clouds at appropriate levels in the atmosphere where the lapse rate is essentially adiabatic. Thus a correct first-order description of the Jovian atmosphere should be given by thermodynamic models, of which the more successful ones are Lewis (1969a, b) and Barshay and Lewis (1978). The presence of C₂H₆ and C₂H₂ at concentrations far in excess of thermodynamic expectations posed no problem, as photo-

chemical processes occurring high in the atmosphere can readily account for their observed abundances (Strobel, 1975).

The detection of PH₃ (Ridgway, 1974) appeared to invalidate the thermodynamic models, since according to Lewis (1969b) PH₃ was removed deep in the atmosphere by condensation as P₄O₆. Prinn and Lewis (1975) invoked rapid convection in the interior to prevent the chemical conversion of PH₃ to P₄O₆ and to transport observable amounts to the tropopause region. Further departures from thermodynamic structure were suggested by Beer's (1975) detection of CO. Prinn and Barshay (1977) have argued that the same rapid convection needed to explain observable amounts of PH₃ will also transport CO up from the 1000°K level where its mixing ratio is $\sim 10^{-9}$, to yield spectro-

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scopically detectable amounts in the Jovian troposphere.

More recent observations and further analysis by Beer and Taylor (1978) indicate a low CO rotational temperature $\sim 125 \pm 25^\circ\text{K}$ and a column density of $4.3_{-2.2}^{+4.3} \times 10^{17} \text{ cm}^{-2}$. As a consequence of its low rotational temperature, CO must be concentrated primarily in the Jovian stratosphere with a mixing ratio $\sim 10^{-8}$ (Beer and Taylor, 1978). Rapid convection cannot concentrate CO preferentially in the stratosphere. Larson *et al.* (1978) have reported similar observations at lower resolution but from the Kuiper Airborne Observatory where telluric CO is a negligible problem. They estimate a column density of $8 \times 10^{17} \text{ cm}^{-2}$ and a rotational temperature of 150 to 300°K , due to the probable detection of high J lines.

While a resolution of this problem requires further observations, we would like to propose an alternative source of CO that concentrates it preferentially in the stratosphere and thus support the Beer and Taylor (1978) analysis that it is stratospheric CO. We argue that material ejected by energetic particles from the Galilean satellites provides a source of oxygen in the upper atmosphere of Jupiter. Subsequent reactions readily lead to formation of CO. The key chemical steps involve the conversion of energetic O^+ ions to either O atoms or OH radicals, followed by a fast reaction with CH_3 radicals to produce CH_2O . Thus some minor constituents in the upper atmosphere of Jupiter may owe their presence to the physical interaction of magnetospheric plasma with the Galilean satellites. This additional complication represents a further departure from an atmosphere of solar composition and thermodynamic distribution.

2. MATERIAL EJECTED FROM GALILEAN SATELLITES

The Galilean satellites are immersed in the intense radiation environment of the

extensive Jovian magnetosphere. The interaction between the tenuous atmospheres or surfaces of the satellites and the energetic particles is believed to be responsible for a number of interesting phenomena. Io, the innermost Galilean satellite, is associated with optical emissions due to the presence of sodium, potassium, and hydrogen atoms in an extended region around the satellite. (Brown, 1974; Trafton, 1975; Judge and Carlson, 1974; see also Brown and Yung, 1976 for review). It is clear that Io is the source of these atoms. Based on recent observations and models we estimate the flux of Na and H from Io's surface to be $\sim 1 \times 10^8$ and $1 \times 10^{10} \text{ atoms cm}^{-2} \text{ sec}^{-1}$, respectively (Carlson and Judge, 1974; Matson *et al.*, 1974; McElroy and Yung, 1975; Smyth and McElroy, 1977). The primary loss process of these neutral atoms is ionization by impact with electrons and protons in the radiation belts. Indeed, Hill and Michel (1976) have proposed that this is a significant source of heavy ions for the magnetosphere. The recent detection of optical emissions associated with ionized sulfur in the vicinity of Io's orbit (Kupo *et al.*, 1976) provides support for Hill and Michel's idea.

Evidence that the other Galilean satellites are sources of particles is less direct. The surfaces of Ganymede, Europa, and Callisto are partially covered with water frost (Pilcher *et al.*, 1972; Lebofsky, 1977). Ganymede is suspected to possess an atmosphere whose surface pressure might be as high as 10^{-3} mbar (Carlson *et al.*, 1973). Yung and McElroy (1977) proposed that an oxygen atmosphere of such magnitude could be derived from the photodissociation of water vapor. The theory predicts an escape flux for oxygen of order $10^8 \text{ atoms cm}^{-2} \text{ sec}^{-1}$ due to photolysis of O_2



Similar atmospheres could exist on Europa and Callisto. Wu *et al.* have tentatively

TABLE Ia

SOURCES OF OXYGEN FROM GALILEAN SATELLITES BASED ON DISCUSSIONS IN SECTIONS 2 AND 3. φ_s IS THE ESTIMATED FLUX OF OXYGEN ATOMS FROM A SATELLITE. φ_J IS THE CORRESPONDING GLOBALLY AVERAGED FLUX OF OXYGEN IONS ENTERING THE UPPER ATMOSPHERE OF JUPITER

Satellite	φ_s ($\text{cm}^{-2} \text{sec}^{-1}$)	φ_J ($\text{cm}^{-2} \text{sec}^{-1}$)	Reference
Io ^a	3×10^9 – 3×10^{10}	1×10^6 – 1×10^7	Smyth and McElroy (1977)
Ganymede	1×10^8	4×10^4	Yung and McElroy (1977)
Ganymede	3×10^7 – 10^{10}	1×10^4 – 4×10^6	Lanzerotti <i>et al.</i> (1978)
Europa	3×10^8 – 1×10^{11}	6×10^4 – 2×10^7	Lanzerotti <i>et al.</i> (1978)
Callisto	2×10^5 – 5×10^7	3×10^2 – 10^4	Lanzerotti <i>et al.</i> (1978)

^a We assume $\varphi_s = 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$ for Na, and assumed that Na/O ratio for the surface of Io ranges from cosmic abundance to a few percent.

identified atomic oxygen on Europa from uv emission observed by Pioneer 11.

A most interesting experiment was recently reported by Brown *et al.* (1978) on the sputtering of ice by energetic ions. The sputtering efficiencies for heavy elements like oxygen were measured to be several orders of magnitudes higher than the values expected on the basis of classical sputtering theory. The significance of this process as a mechanism for the erosion of water ice and other heavy elements has been discussed by Lanzerotti *et al.* (1978). The authors concluded that based on the current knowledge of the Jovian magnetosphere (Trainer *et al.*, 1974; Frank *et al.*, 1976; Shawhan *et al.*, 1975) the erosion rates of H₂O should fall in the range 3×10^7 to 1×10^{10} , 3×10^8 to 1.0×10^{11} , and 2×10^5 to 5×10^7 molecules $\text{cm}^{-2} \text{sec}^{-1}$ for Ganymede, Europa, and Callisto, respectively.

3. HEAVY IONS IN THE MAGNETOSPHERE AND UPPER ATMOSPHERE

The neutral atoms and molecules ejected from the Galilean satellites are readily ionized by particle bombardment, with a time constant of less than a week, and swept away by the magnetic field of Jupiter. The fate of these heavy ions which have a mean residence time of order 1 year in the magnetosphere has been investigated by Siscoe and Chen (1977) and Siscoe (1978). They undergo random motions

across the magnetic field lines, and ultimately the ions diffuse inward towards Jupiter, or outward and become lost by interaction with solar wind. The fraction of ions that diffuse inward has been shown by Siscoe (1978) to be 0.52, 0.41, 0.29, and 0.17 for Io, Ganymede, Europa, and Callisto, respectively.² Conservation of the first adiabatic invariant implies that an oxygen ion from Io would arrive at Jupiter with of order 65 keV of energy, while the respective energies from Europa, Ganymede, and Callisto are 0.85, 12, and 190 MeV. The energetic oxygen ions are stopped in the atmosphere primarily as O⁺, O, or OH. The altitude where this process occurs can be estimated by Lindhard-Scharff-Schiott (LSS) theory originally developed for projected ion ranges in semiconductors (Johnson and Gibbons, 1970). The latitude where this process occurs is immaterial, since the CO lifetime in the Jovian atmosphere is sufficient to insure horizontal homogeneity.

Table Ia summarizes the fluxes of available oxygen atoms escaping the Galilean satellites, and the corresponding fluxes of oxygen ions entering Jupiter. Table Ib can be used to calculate the level of the atmosphere where most of the ions are stopped. Since the major flux contributions are from Io and Europa, the total

² Siscoe (private communication, 1978) informed us that these values should be regarded as lower limits.

TABLE Ib

PROJECTED RANGES FOR AN OXYGEN ION IN AN H₂ ATMOSPHERE BASED ON LSS THEORY. E , $L(E)$, AND N , RESPECTIVELY, DENOTE ENERGY OF AN OXYGEN ION, TOTAL LOSS FUNCTION, AND COLUMN AMOUNT OF H₂ REQUIRED TO STOP THE ION

E (keV)	$L(E)$ (eV cm ²)	N (cm ⁻²)
10	1.1×10^{-14}	8.4×10^{17}
100	1.2×10^{-14}	9.3×10^{18}
1000	3.1×10^{-14}	5.1×10^{19}

loss functions were only computed up to 1 MeV. For each order of magnitude increase in ion energy beyond 1 MeV, the ions can penetrate an additional 3 to 4 scale heights deeper into the atmosphere.

4. CHEMICAL FORMATION OF CO IN THE ATMOSPHERE

From the discussion given in the previous section and Table Ib, we may conclude that the precipitating energetic O⁺ ions, which come primarily from Io and Europa, are stopped in the upper atmospheric region below the main ionspheric peak ($[H_2] \sim 10^{11} \text{ cm}^{-3}$) and above the mesopause ($[H_2] \sim 5 \times 10^{13} \text{ cm}^{-3}$; Strobel and Smith, 1973). Based on the most recent measurements of Ly- α (Giles *et al.*, 1976; Atreya *et al.*, 1977) that yielded $\sim 2kR$, the analysis of Wallace and Hunten (1973) would suggest an eddy diffusion coefficient of $K = 1-2) \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$ and locate the turbopause or homopause at a density level $[H_2] \sim 10^{13} \text{ cm}^{-3}$, approximately the region where the energetic O⁺ ions are thermalized. At this altitude the approximate transport time constant (H_2/K) is $\sim 6 \times 10^6 \text{ sec}$ for an atmospheric scale height of $\sim 30 \text{ km}$.

At 100 keV the most probable fate of O⁺ ions is a transfer of charge with the dominant H₂ molecules. The resulting energetic O atoms may be stripped of an electron and then charge transfer with H₂. Based on the experimental work of Jorgensen *et al.* (1965) below 100 keV, the beam

would consist primarily of neutral O atoms. At thermal energies the reaction $O + H_2 \rightarrow OH + H$ is negligible (Hampson and Garvin, 1975) and a cold, thermal O atom at the Jovian turbopause will react preferentially with CH₃ radicals to form CH₂O,

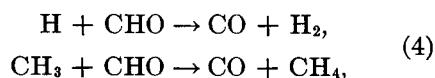


$k \sim 1.3 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$ (Hampson and Garvin, 1975). Before thermalization the O atom may react with H₂ to form OH. Since OH reacts also preferentially with CH₃



($k \sim 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$; D. J. Bogan, private communication, 1978) rather than with H₂ ($k \sim 10^{-18} \text{ cm}^3 \text{ sec}^{-1}$ at 150°K; Hampson and Garvin, 1975), the net product is the same. These estimates are made with the density profiles given in Strobel (1974). Some justification for the products of (3) is in order. This reaction leads to the formation of a vibrationally excited intermediate CH₃OH*. Bialkowski and Guillory (1977) used a CO₂ laser to initiate infrared multiphoton dissociation of CH₃OH and found that $\sim 90\%$ of the dissociation events yielded CH₂O + H₂, and the rest of the events, OH + CH₃. Since multiphoton infrared absorption vibrationally excites CH₃OH, the laboratory study lends support to the assumed products in (3).

Reactions of O and OH with other abundant hydrocarbons were considered, but found to be substantially slower than reactions (2) and (3). Once CH₂O is formed it readily dissociates ($J \sim 7 \times 10^{-6} \text{ sec}^{-1}$; Calvert and Pitts, 1966) to yield CO or CHO. The latter radical reacts rapidly with either H or CH₃ to generate more CO

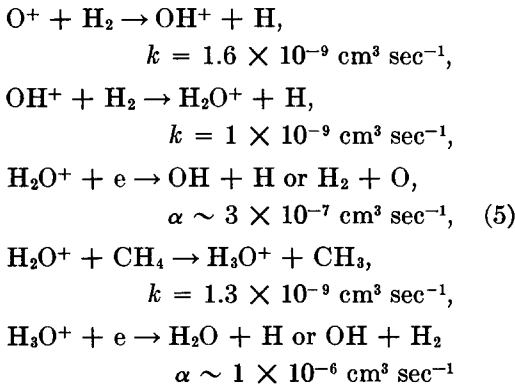


$k \sim 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$ (Engleman, 1976).

At the level of CO formation most solar euv radiation below 850 Å has been absorbed and CO has a lifetime against dis-

sociation of $>10^8$ sec, which considerably exceeds the mixing time constant. In the Jovian stratosphere all solar radiation capable of dissociating CO has effectively been observed by CH₄ at higher altitudes. As a consequence CO is photochemically stable in the Jovian atmosphere.

A minor fraction of the incident O⁺ ions will be lost by reactions with H₂. At very low energies the dominant reactions which must be considered are



(Huntress, 1977; Leu *et al.*, 1973). Unfortunately the products of the dissociative recombination reactions are unknown. In the event that H₂O is formed by H₃O⁺ + e we note that H₂O has a dissociative lifetime of $\sim 10^7$ sec which is considerably less than the transport time down to the tropopause. Thus H₂O has a high probability of repeated dissociation as it is mixed down to the stratosphere. The O and OH products will form CO by the chain of reactions discussed in this section. In the event that reaction (3) is considerably slower than estimated above it should be noted that OH reacts sufficiently fast with C₂H₂ and C₂H₄ to form C₂H₂O and C₂H₄OH, respectively (Davis *et al.*, 1975). Subsequent dissociation yields CO and CH₂O, respectively. These reactions would also be effective in CO production from O⁺ ions with energies greater 10 MeV that penetrate below the main layer of CH₃ radicals in the Jovian atmosphere. Hence most energetic O⁺ ions incident on the Jovian

atmosphere will be chemically converted to CO.

5. THE VERTICAL DISTRIBUTION OF CO

The vertical density profile of CO is determined by the continuity equation

$$d\varphi/dz \simeq P, \quad (6)$$

where

$$\varphi \simeq -K(dn/dz + n/H), \quad (7)$$

φ is the CO flux, P is its production rate, and n is the density. As previously discussed, the CO dissociation rate is negligible and below the mesopause $P \sim 0$. From (6), φ must be a constant, $-\varphi_0$, where the minus sign indicates downward flow. The magnitude of φ_0 is given approximately by the integrated production of CO which is equal to the flux of entering O⁺ ions listed in Table Ia. Let us consider a specific case of $\varphi_0 = 2 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ and take the $z = 0$ level as the tropopause where $[\text{H}_2] \sim 6 \times 10^{18} \text{ cm}^{-3}$. In the upper troposphere mixing processes are fast and $K = K_t \gtrsim 10^7 \text{ cm}^2 \text{ sec}^{-1}$ is an appropriate value (Prinn and Owen, 1976). Above the tropopause we assume that

$$K = K_s \exp(z/2H). \quad (8)$$

based on arguments presented by Lindzen (1971). From analogy with the Earth's stratosphere we expect K_s to be substantially smaller than the tropospheric value (Huntten, 1975). Estimates for K_s range from 2×10^2 (Sagan and Salpeter, 1976) to $2 \times 10^4 \text{ cm}^2 \text{ sec}^{-1}$ (Strobel, 1973).

Above the tropopause integration of (7) with $\varphi = -\varphi_0$, and (8) yields

$$n_s = (2\varphi_0 H / K_s) \exp(-z/2H) \quad (9)$$

for a high altitude source and a low altitude sink (in the Jovian interior) for CO. Below the tropopause the equivalent solution is

$$n_t = \varphi_0 H / K_t. \quad (10)$$

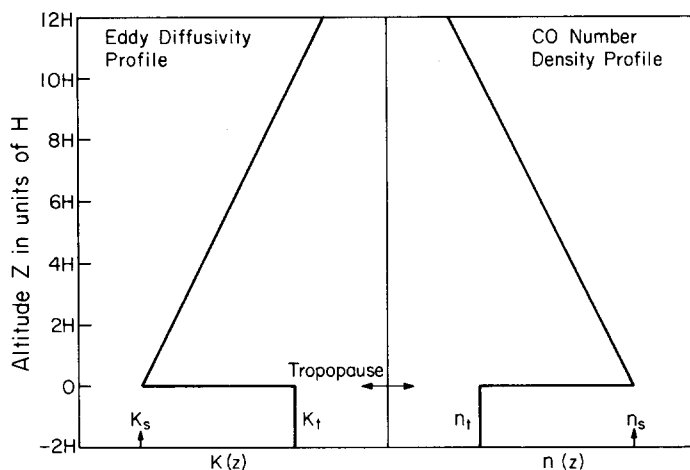


FIG. 1. Characteristic eddy diffusion profile $K(z)$ and CO number density profile $n(z)$ in the Jovian upper atmosphere. The tropopause is taken to be the level $z = 0$. K_t , K_s respectively denote the magnitude of the eddy diffusion coefficient in the troposphere and the stratosphere. The number densities $n_t = \varphi_0 H / K_t$, $n_s = 2 \varphi_0 H / K_s$, where H is the scale height and φ_0 is the flux of oxygen atoms entering the upper atmosphere of Jupiter.

At $z = 0$,

$$n_s/n_t = 2(K_t/K_s) \gg 1,$$

and thus most of the CO is in the stratosphere. The CO column density, N , is

$$N = \int_0^{\infty} n_s dz = 4 \varphi_0 H^2 / K_s. \quad (11)$$

For $\varphi_0 = 2 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$, $H = 20 \text{ km}$, and $K_s = 10^3 \text{ cm}^2 \text{ sec}^{-1}$,

$$N \simeq 6 \times 10^{17} \text{ cm}^{-2}$$

in reasonable agreement with the observed abundances (Beer and Taylor, 1978; Larson *et al.*, 1978). The above discussion is summarized in Fig. 1.

Unfortunately there is considerable uncertainty in previous estimates for K_s and the CO column density varies inversely proportional to K_s . Strobel (1973) and Tomasko (1974) derived an effective NH_3 scale height of $H_{\text{eff}} \sim 3 \text{ km}$ from uv albedo measurements under the assumption that photochemical destruction and vertical mixing determined its altitude distribution. For this case

$$K_s \sim H_{\text{eff}}^2 \epsilon J,$$

where J is the NH_3 dissociation rate and ϵ is the fraction of NH_3 irreversibly destroyed. While J can be accurately calculated, ϵ depends on complex chemical reactions, for which only a paucity of data is available. Strobel (1977) pointed out various scenarios for NH_3 - PH_3 photochemistry that could lead to a factor of 10 change in ϵ . The presence of C_2H_2 as a radical scavenger would further complicate the chemistry (Vera Ruiz and Rowland, 1978).

The Sagan and Salpeter (1976) estimate for K_s is based on the fact that the adiabatic cooling rate associated with motions that control mixing cannot exceed the total radiative heat flux and the assumption of a height variation of $\exp(z/H)$ for K . Their upper limit for K_s is $7 \times 10^5 \text{ cm}^2 \text{ sec}^{-1}$. By adopting a value of $K \sim 3 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$ at $[\text{H}_2] \sim 1.5 \times 10^{13} \text{ cm}^{-3}$ (Wallace and Huntten, 1973; Carlson and Judge, 1974), they obtained $K_s \sim 2 \times 10^2 \text{ cm}^2 \text{ sec}^{-1}$ at the 0.5-atm level ($[\text{H}_2] \sim 3 \times 10^{19} \text{ cm}^{-3}$). At the temperature minimum (which we define as the tropopause in contraction to their definition) $K \sim 10^3$

$\text{cm}^2 \text{sec}^{-1}$. In conclusion there is considerable uncertainty in the magnitude of K_s , but a value of $10^3 \text{cm}^2 \text{sec}^{-1}$ cannot be ruled out by present evidence.

6. CONCLUSION

We have demonstrated the possible importance of the Galilean satellites as a source of oxygen for the upper atmosphere of Jupiter. Accumulation of CO would occur preferentially in the stratosphere, in support of the observational interpretation by Beer and Taylor (1978), but not consistent with that by Larson *et al.* (1978). An O atom input flux, $\varphi_0 \sim 10^7 \text{cm}^{-2} \text{sec}^{-1}$, and a tropopause coefficient, $K_s \sim 10^3 \text{cm}^2 \text{sec}^{-1}$, are required to obtain the observed CO abundance. The present work on CO has obvious implications for the accumulation of other heavy elements in the Jovian upper atmosphere. Using the current estimates for sodium flux from Io, we predict a column abundance of order 10^{14}cm^{-2} for sodium atoms, a concentration sufficiently high to be observable by spectroscopic techniques. There could be as much as 10^{15} , and 10^{16} atoms of S and Si, respectively, as well as smaller concentrations of K, Mg, and Al, expected on the basis of cosmic abundances. In the case of S, which is chemically similar to O, we suggest that it will accumulate predominantly as CS.

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