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Stability of an Oxygen Atmosphere on Ganymede

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Photolysis of water and subsequent escape of hydrogen can give rise to an oxygen atmosphere on Ganymede. Growth of the atmosphere may be limited by escape of fast oxygen atoms formed by photodissociation of O_2. Escape of oxygen and hydrogen in an equilibrium configuration should balance net evaporation of water from the satellite's surface and the partial pressure of atmospheric O_2 could be as high as 10^{-3} mbar. Ganymede should have lost an appreciable quantity of water over geologic time, enough to have coated the surface of the satellite with ice to a depth of about 2 m. An oxygen atmosphere with similar properties might be expected to occur also on Callisto.

1. INTRODUCTION

Ganymede, the largest of Jupiter's Galilean satellites, is thought to have a thin atmosphere whose surface pressure might be at least as large as 10^{-3} mbar (Carlson *et al.*, 1973). The composition of the atmosphere is unknown, though the presence of water ice on the surface (Pilcher *et al.*, 1972) can be taken to provide an important clue.

Water vapor may be dissociated at wavelengths below 2400 Å and subsequent chemistry would be expected to lead to a significant source of molecular oxygen. The gas could form heterogeneously on the surface, or homogeneously in the atmosphere by reactions such as

$$OH + OH \rightarrow H_2O + O \qquad (1)$$

followed by

$$O + OH \rightarrow O_2 + H. \qquad (2)$$

Hydrogen would escape readily at temperatures prevalent on Ganymede and the initial growth rate for O_2 could be as large as 10^8 molecules cm^{-2} sec^{-1}. An atmosphere with a surface pressure as high as 10^{-3} mbar could develop in a period as short as 10^4 yr. The source of oxygen would decline as the atmosphere became optically thick at wavelengths which dissociate H_2O.

We shall argue that the system should approach a steady state in which production of O_2 by (2) should be balanced by escape of O, with fast atoms released by photodecomposition of exospheric O_2. In equilibrium, Ganymede's atmosphere might contain concentrations of O_2 similar to those present on Mars (Carleton and Traub, 1972), and might also include a large and perhaps detectable concentration of O_3.

Details of the equilibrium model are developed in Section 2. Results are presented and discussed in Section 3.

2. MODEL

As noted above, we expect the chemical evolution of Ganymede's atmosphere to be driven by dissociation of H_2O,

$$h\nu + H_2O \rightarrow OH + H. \qquad (3)$$

Hydrogenous radicals would be removed either by

$$H + HO_2 \rightarrow H_2 + O_2 \qquad (4)$$

or by

$$OH + HO_2 \rightarrow H_2O + O_2, \qquad (5)$$

and O_2 should be formed mainly by (2).

Oxygen would be recycled by

$$h\nu + O_2 \rightarrow O(^1D) + O(^3P) \qquad (6)$$

and by

$$h\nu + O_2 \rightarrow O(^3P) + O(^3P) \qquad (7)$$

and reactions (6) and (7) should provide an important energy source to feed escape of oxygen. It is clear that exospheric oxygen atoms can escape Ganymede's gravitational field if their initial velocity vectors are oriented in the upward hemisphere and if their energies exceed about 0.63 eV. Reactions (6) and (7) can impart sufficient energy for escape if the incident photons have wavelengths below 1530 and 2020 Å, respectively.

The escape rate, in atoms cm^{-2} sec^{-1}, is given by

$$\phi_O{}^e = J_{O_2}{}^e N_{O_2}{}^e, \qquad (8)$$

where $N_{O_2}{}^e$ is the column density of O_2 (cm^{-2}) above the critical level, and $J_{O_2}{}^e$ is a frequency factor (sec^{-1}) defined by

$$J_{O_2}{}^e = \int_0^{1530\,\text{Å}} (\pi F_\lambda) Q^6{}_\lambda d\lambda + \int_0^{2020\,\text{Å}} (\pi F_\lambda) Q^7{}_\lambda d\lambda. \qquad (9)$$

Here πF_λ denotes the spatially averaged solar flux (photons cm^{-2} sec^{-1} per unit wavelength) at wavelength λ; $Q_\lambda{}^{6,7}$ are the cross sections (cm^2) for reactions (6) and (7).

We consider a relatively simple model for Ganymede's atmosphere, an isothermal gas at a temperature of 140°K. We assume that the vapor pressure of H_2O is set by the temperature of the underlying surface, which is taken to satisfy the condition of local radiative equilibrium. Average temperatures are presented as a function of latitude in Table I, which also includes corresponding values for the partial pressure of H_2O estimated using the analysis described by Weidenschilling and Lewis (1973). The Bond albedo was set equal to 0.32 as recommended by Morrison and Cruikshank (1974) and the planetary average value for the partial pressure of H_2O was estimated to be about 7.5×10^{-9} mbar using an insolation-weighted mean of the data in Table I.

TABLE I

Temperature and Partial Vapor Pressure of Water as Computed for Various Latitudes on Ganymede

Latitude (deg)	Temperature (°K)	P_{H_2O} (mbar)
5	146.7	7.0×10^{-8}
15	145.5	5.0×10^{-8}
25	142.9	2.5×10^{-8}
35	139.0	8.0×10^{-9}
45	133.4	1.5×10^{-9}

Solar fluxes were taken from Brinkmann *et al.* (1966) and data for various reactions of importance in the hydrogen oxygen system are summarized in Table II. Concentrations of H, OH, HO_2, H_2O_2, $O(^3P)$, $O(^1D)$, O_2, and O_3 were obtained by solving an appropriate set of reaction equations. The numerical scheme allowed for vertical transport of O, H, H_2, and H_2O. The influence of dynamics at lower altitudes was modeled using the expedient concept of eddy diffusion with the diffusion coefficient, K, set equal to 10^7 cm^2 sec^{-1}. Results are relatively insensitive, however, to the choice of K since molecular diffusion plays a dominant role over most of the height range considered here.

The surface was assumed to be chemically passive. Fluxes of O, H, and H_2 were set equal to zero at the lower boundary. The surface was taken to provide a net source of H_2O whose magnitude is precisely that required to balance escape of H and O from the exosphere.

TABLE II

Reactions and rate constants for the hypothetical H_2O–O_2 atmosphere on Ganymede[a]

Reaction	Rate
$O_2 + h\nu \rightarrow O + O$	$J_1 = 9.1 \times 10^{-8}$
$H_2O + h\nu \rightarrow H + OH$	$J_2 = 1.7 \times 10^{-7}$
$H_2O_2 + h\nu \rightarrow 2OH$	$J_3 = 2.1 \times 10^{-6}$
$O_3 + h\nu \rightarrow O_2 + O(^1D)$	$J_4 = 1.7 \times 10^{-4}$
$O_2 + h\nu \rightarrow O + O(^1D)$	$J_5 = 9.0 \times 10^{-8}$
$O_2 + h\nu(\lambda < 1530\ \text{Å}) \rightarrow O(^3P) + O(^1D)$	$\left.\begin{matrix}J_6\\J_7\end{matrix}\right\} J_{O_2}{}^{e} = 4.8 \times 10^{-8}$
$O_2 + h\nu(\lambda < 2020\ \text{Å}) \rightarrow O(^3P) + O(^3P)$	
$O(^1D) + H_2O \rightarrow OH + OH$	$K_1 = 3.0 \times 10^{-10}$
$O(^1D) + H_2 \rightarrow OH + H$	$K_2 = 2.0 \times 10^{-10}$
$O + O + O_2 \rightarrow O_2 + O_2$	$K_3 = 2.0 \times 10^{-34} e^{710/T}$
$H + O_2 + O_2 \rightarrow HO_2 + O_2$	$K_4 = 1.8 \times 10^{-32} e^{342/T}$
$O + HO_2 \rightarrow OH + O_2$	$K_5 = 7.0 \times 10^{-11}$
$H + O_3 \rightarrow OH + O_2$	$K_6 = 2.6 \times 10^{-11}$
$O + O_2 + O_2 \rightarrow O_3 + O_2$	$K_7 = 1.1 \times 10^{-34} e^{520/T}$
$O + OH \rightarrow O_2 + H$	$K_8 = 5.0 \times 10^{-11}$
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	$K_9 = 9.5 \times 10^{-12}$
$H + HO_2 \rightarrow H_2 + O_2$	$K_{10} = 1.0 \times 10^{-11}$
$OH + HO_2 \rightarrow H_2O + O_2$	$K_{11} = 2.0 \times 10^{-10}$
$H + HO_2 \rightarrow OH + OH$	$K_{12} = 3.0 \times 10^{-11}$
$H + H + O_2 \rightarrow H_2 + O_2$	$K_{13} = 2.6 \times 10^{-32}$
$OH + OH \rightarrow H_2O + O$	$K_{14} = 2.6 \times 10^{-12}$
$O(^1D) + O_2 \rightarrow O(^3P) + O_2$	$K_{15} = 5.0 \times 10^{-11}$

[a] The units for mean photolysis rates (J), two-tody and three-body reactions (K) are sec^{-1}, $cm^3\ sec^{-1}$, and $cm^6\ sec^{-1}$, respectively. Numerical values for J_1 through J_7 apply under optimum conditions, i.e., at sufficiently high altitudes. This table is taken from Sze and McElroy (1975), updated to allow for some more recent information.

3. RESULTS AND DISCUSSION

Results for lower regions of the atmosphere are shown in Fig. 1. Molecular oxygen is the major component of the atmosphere, followed by H_2O, H_2, O, O_3, H, OH, HO_2, and H_2O_2. The surface

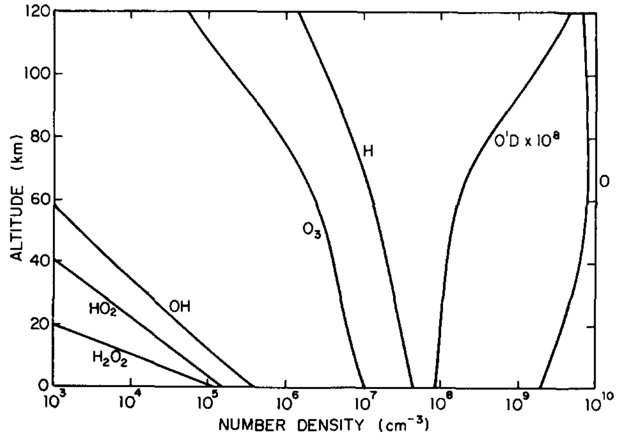

Fig. 1. Number density of H, OH, HO_2, H_2O_2, O, $O(^1D)$ and O_3 in Ganymede's lower atmosphere. The surface pressure of O_2 is 1×10^{-3} mbar. The surface value for the partial pressure of H_2O is set equal to 7.5×10^{-9} mbar.

pressure is about 10^{-3} mbar and oxygen acts as an efficient shield for ultraviolet solar radiation below 2400 Å, limiting the net rate for dissociation of H_2O.

This photolysis rate for H_2O is shown as a function of the partial pressure for O_2 in Fig. 2. Here L_0 defines the dissociation rate for H_2O,

$$L_0 = \int_0^\infty J_2(z)[H_2O]dz \qquad (10)$$

and curve L gives the net dissociation

$$L = L_0 - \int_0^\infty k_{11}[OH][HO_2]dz. \qquad (11)$$

In the present scheme L provides a direct measure of the escape rate for O. The escape rate for H is larger by a factor of 2, consistent with our assumption that the atmosphere should approach a steady state.

Figure 2 allows an important insight into the manner in which Ganymede's atmosphere might be expected to approach its final stable configuration. In the initial stages of evolution hydrogen should escape rapidly. Escape of oxygen would be expected to lag somewhat, limited by the available source of O_2. The escape rate of O should rise to an asymptotic value of about 4.2×10^7 atoms cm^{-2} sec^{-1}, as the column density of O_2 approaches 10^{15} molecules cm^{-2}, i.e., as the satellite acquires a full exospheric complement of O_2. Escape of hydrogen should continue to exceed that for O, and the O_2 content of the atmosphere should rise steadily. The growth rate for O_2 should dimenish slowly as the atmosphere becomes optically thick at wavelengths below 2400 Å, as shown in Fig. 2. Finally the system should approach an equilibrium configuration with $L = \phi_O = \frac{1}{2}\phi_H$, where ϕ_O and ϕ_H denote the escape fluxes for H and O, respectively.

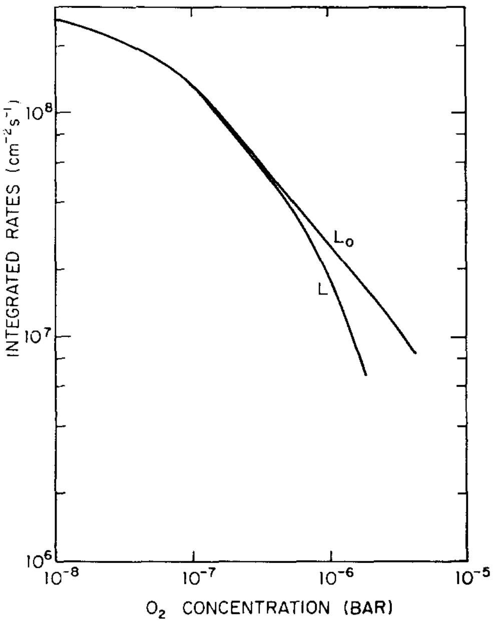

FIG. 2. Dissociation rate, L_O, and net dissociation rate for H_2O as a function of surface pressure of O_2. The surface pressure of H_2O is set equal to 1×10^{-8} mbar.

The stability of the system may be readily verified. A decrease in O_2 would expose more H_2O to sunlight below 2400 Å. The dissociation rate for H_2O would rise accordingly with a consequent increase in the effective rate for production of O_2. On the other hand, an increase in O_2 would cause a decrease in the source of hydrogen radicals, with a corresponding drop in the supply of H to the exosphere. Molecular hydrogen acts as an efficient buffer in this system. The source of H_2 and consequently hydrogen escape can adjust readily to small changes in the concentration of O_2.

Densities computed for the upper atmosphere are shown in Fig. 3. The atmosphere contains a relatively large concentration of O. The airglow intensity at 1304 Å could be as great as 30 R, if we adopt formulas quoted by Stewart (1970). Ganymede should have a Lyman α halo with an intensity approaching 2 kR formed by resonance scattering of sunlight by H atoms. The circum-Jovian space near Ganymede's orbit could contain as many as 10^{33} molecules of H_2, with comparable

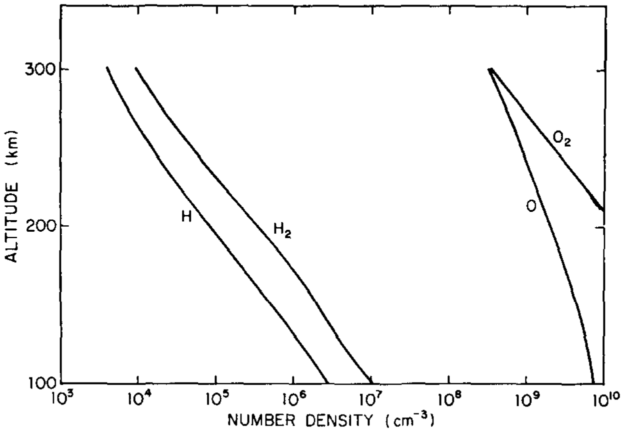

FIG. 3. Number density of H, H_2, O, and O_2 in the upper atmosphere. Assumptions are the same as for Fig. 1. The exobase is at 300 km.

numbers of H and O atoms if we assume a lifetime of about 10 yr for each species. Ganymede could have a significant ionosphere, with a maximum number density as high as 2×10^4 formed by photoionization of O and O_2. The interaction of this ionosphere with Jupiter's magnetosphere would provide an interesting topic for further study.

The results described above apply for a particular concentration of atmospheric H_2O. Figures 4 and 5 show results from a study in which the partial pressure of H_2O was set equal to 2.5×10^{-9} mbar at the surface. The equilibrium model for the atmosphere is somewhat less dense in this case. The computed value for the partial pressure of O_2 is lowered by about a factor of 2.5 from 1×10^{-3} (number density $= 5 \times 10^{13}$ cm^{-3}) to 4×10^{-4} mbar (number density $= 2 \times 10^{13}$ cm^{-3}).

The effect of a change in the concentration of atmospheric H_2O may be readily interpreted using information summarized in Fig. 2. It is difficult to escape the conclusion that Ganymede should have an appreciable atmosphere of oxygen. This result should hold for all models in which

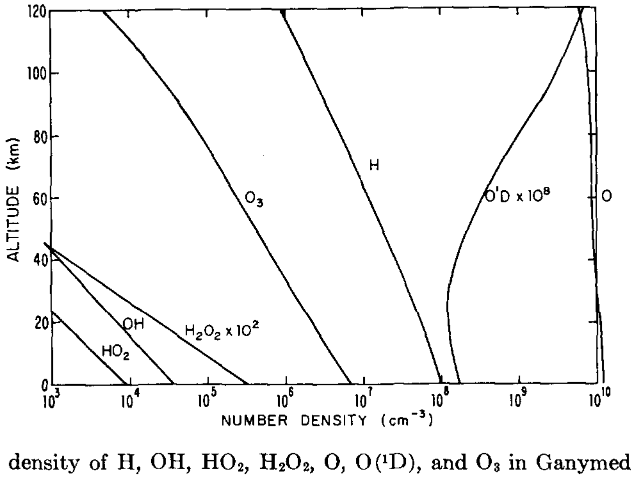

FIG. 4. Number density of H, OH, HO_2, H_2O_2, O, $O(^1D)$, and O_3 in Ganymede's lower atmosphere. The surface pressure of O_2 is 4×10^{-4} mbar. The surface value for the partial pressure of H_2O is set equal to 2.5×10^{-9} mbar.

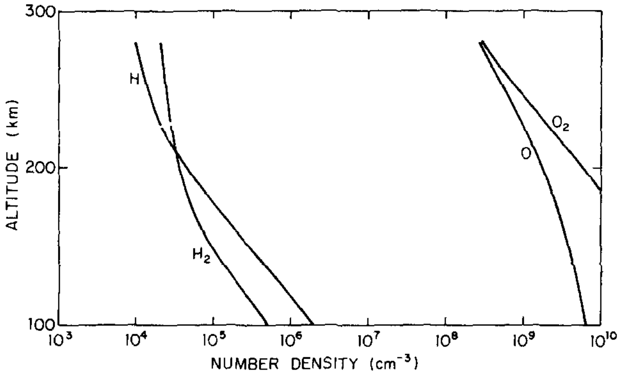

FIG. 5. Number density of H, H_2, O, and O_2 in the upper atmosphere. Assumptions are the same as for Fig. 4. The exobase is at 280 km.

the average value for the partial pressure of atmospheric H_2O should exceed about 2×10^{-9} mbar. It should not be affected to any great extent by details of the chemical model summarized in Table II. A downward revision of the rate constant for K_{11} would tend to reinforce the arguments for an oxygen atmosphere. If K_{11} were decreased by a factor of 10, the partial pressure of O_2 would rise by about a factor of 3. With a lower value for K_{11} one would expect a significant atmosphere of O_2 even if the partial pressure of H_2O should fall appreciably below 2×10^{-9} mbar.

4. CONCLUDING REMARKS

The considerations outlined here may apply also to several of the other Galilean satellites. As much as 80% of the surface of Europa is thought to be covered with water frost and the spectrum of Callisto also shows clear evidence for H_2O. The large concentrations of H_2O on Europa would tend to suppress the formation of O_2. The high albedo of that satellite, a consequence of its extensive ice cover, should inhibit evaporation of H_2O and one would expect the dissociation rate for H_2O on Europa to be significantly less than that for Ganymede. Callisto is more promising. The ice cover in this case is only partial, about 10%. The surface temperature should be somewhat larger than for Europa. Partial pressures of atmospheric H_2O could be relatively high and an appreciable atmosphere could form on Callisto.

The difference observed between the ice covers of the various Galilean satellites poses an interesting problem for any attempt to reconstruct the evolution of the Jovian system. Lewis (1972) thought that water ice should be abundantly present on all of the Galilean satellites, if these satellites were to form at temperatures which might be expected to characterize local regions of the solar nebula. The reflection spectrum of Io however, shows no sign of water ice and as noted above the concentration of ice on the surface of the other satellites appears to be quite variable. An evolutionary model by Pollack and Reynolds (1974) provides a possible solution to this puzzle. They argue that Jupiter during the earlier stages of its evolution might have behaved more like a protosun than a protoplanet. The Jovian heat source could have been quite intense at orbits of Io and Europa. These bodies might have lost from the outset a major fraction of their potential initial store of volatiles. Europa could have acquired its surface ice cover at some later time, associated perhaps with a second evolutionary phase in which residual volatile elements might have been released from the interior following intense heating due to the decay of radioactive nuclei. The satellites Ganymede and Callisto would be relatively unaffected by the primordial heat wave and one might expect these bodies to have retained a large concentration of H_2O.

Further studies of the surface and atmospheric properties of the Galilean satellites may be expected to provide invaluable information on the early history of the Jovian system. An oxygen atmosphere on either Ganymede or Callisto could provide an unexpected bonus—an opportunity to observe chemical processes which might have played an important role in regulating the rise of oxygen on the early prebiotic Earth.

ACKNOWLEDGMENT

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