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Hot oxygen corona at Europa

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Abstract. A model of the hot oxygen exosphere at Europa was constructed. The source term for the hot atoms was assumed to be dissociative recombination of O_2^+ and Liouville's theorem was used to calculate their altitude distribution. It was found that near the surface the hot oxygen density is in excess of 200 cm^{-3}, dropping to a value on the order of 50 cm^{-3} at 1500 km. These calculations indicate that the hot atomic oxygen densities are considerably less than the thermal molecular oxygen ones, but slightly larger than the measured sodium values. The escape flux of the hot oxygen atoms was calculated to be on the order of 1.4×10^{8} atoms cm^{-2} sec^{-1}. This corresponds to a global escape rate of 4.4×10^{25} atoms sec^{-1}, which is more than an order of magnitude less than the estimated atmospheric sputtering rate.

Introduction

During the last few years a number of different observations conclusively established the presence of a tenuous atmosphere (exosphere) around Europa. HST observations of the two OI features at 130.4 and 135.6 nm led to an estimate of a column density of 1.5×10^{15} cm^{-2} for O_2 [*Hall et al.*, 1995]. An extended sodium atmosphere around Europa was also found by *Brown and Hill* [1996] using ground-based optical measurements of the sodium D_1 and D_2 lines. They estimate a column density of about 2×10^{9} cm^{-2} from near the surface and a surface density of 70 cm^{-3}. Radio occultation measurements with the Galileo satellite [*Kliore et al.*, 1997] established the presence of an ionosphere with a mean peak density of about 10^4 cm^{-3} at the surface. *Kliore et al.* [1997] argued that the most likely interpretation of these ionospheric observations is that the major ion is O_2^+ and that the surface neutral O_2 density is about 10^7 cm^{-3}, with a scale height of about 120 km. (Note that the electron impact ionization rates given by *Schreier et al.* [1993], and used by *Kliore et al.* [1997] are too low by nearly a factor of ten, thus the neutral density values arrived at in *Kliore et al.* [1977] must be reduced accordingly.) The presence of significant O_2^+ densities at Europa implies that an extended hot atomic oxygen corona around Europa must exist, similar to that at Venus and Mars [e.g. *Nagy and Cravens*, 1988; *Nagy et al.*, 1990]. The escape energy of oxygen atoms at the surface of Europa is 0.35 eV, thus effectively all newly created and outward moving hot oxygen atoms will escape.

Model Calculations

In this paper we present the results of our calculations of this hot atomic oxygen exosphere at Europa, assuming that dissociative recombination of O_2^+, indicated below by equation (1), is the main source of these atoms:

$$\begin{aligned} O_2^+ + e &\rightarrow O(^3P) + O(^3P) + [6.99\,\text{eV}] && (0.22) \\ &\rightarrow O(^3P) + O(^1D) + [5.02\,\text{eV}] && (0.42) \\ &\rightarrow O(^1D) + O(^1D) + [3.06\,\text{eV}] && (0.31) \\ &\rightarrow O(^3P) + O(^1S) + [2.80\,\text{eV}] && (< 0.01) \\ &\rightarrow O(^1D) + O(^1S) + [0.84\,\text{eV}] && (0.05) \end{aligned} \quad (1)$$

where, the square brackets denote the excess energy and the round brackets show the branching ratios for the vibrational ground state [*Kella et al.*, 1997]. Most of the hot oxygen will be produced within about the first ion scale height, which was estimated by *Kliore et al.* [1997] to be about 240 km. Therefore nearly all (~90%) the atoms moving in the downward hemisphere will reach the surface and likely be lost.

In order to estimate the location of the exobase we need to calculate the mean free path of atomic oxygen in a background of molecular oxygen. There is very little information available on the relevant cross section. Assuming hard sphere collisions, we can estimate the cross section to be on the order of about 5×10^{-15} cm^2, which in turn leads to a mean free path of 1.33×10^{7} cm at the surface, which is slightly larger than the corresponding scale height. Thus it is reasonable to assume, for our calculations, that the entire atmosphere above the surface is an exosphere. However it is an unusual type of "exosphere" in which the source of particles is not from below but from within the region. We adopted a surface O_2^+ density of 10^4 cm^{-3} and a plasma scale height of 240 km. The total dissociative recombination rate of O_2^+, k_1, was taken to be [*Mehr and Biondi*, 1969; *Alge et al.*, 1983]:

$$\begin{aligned} k_1 &= 1.95\times10^{-7}\{300/T_e\}^{0.7} && \text{for } T_e < 1200°K \\ &= 7.38\times10^{-8}\{1200/T_e\}^{0.56} && \text{for } T_e > 1200°K \end{aligned} \quad (2)$$

and the electron temperature was assumed to be 610°K, the plasma and neutral temperature values deduced by *Kliore et al.* [1997] from the observed electron density scale height. These observations do place some constraints on the temperatures,

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even though the densities are not expected to be in diffusive equilibrium. The neutral density scale height deduced by *Kliore et al.* [1997] from the electron density observations is close to the one obtained from model calculations by *Saur et al.* [1998]. At the lower altitudes, where most of the hot oxygen production takes place, the electron temperature is likely to be close to the neutral one, but at higher altitudes, it should increase rapidly due to a number of factors, such as energy input from Jupiter's magnetosphere carried in by torus electrons. The reaction rate for dissociative recombination is inversely proportional to the electron temperature, but our assumed electron temperature, even if we underestimated it, should not introduce significant uncertainties in the calculated hot oxygen densities. We assumed that the hot oxygen atoms are created isotropically with half of them moving upward, and that the downward moving atoms are lost at the surface and are not backscattered, as mentioned earlier. The densities were calculated, using Liouville's theorem [e.g. *Banks and Kockarts*, 1973], which provides a relationship between the distribution functions at different radial distances in an exosphere. We started the calculations at the assumed exobase, at the surface of Europa, and used 2-km altitude increments in adding the newly created hot oxygen atoms into these exospheric calculations. We did this up to an altitude above which the production rate was small enough so that the calculated densities changed by less than 0.1%. The calculated densities are shown in Figure 1.

Discussion

As can be seen, there is a significant hot oxygen corona with densities that decrease with altitude from a value in excess of 200 cm^{-3} at the surface. The calculated escape flux of atomic oxygen is 1.4×10^8 atoms cm^{-2} sec^{-1}, for an assumed electron temperature of 610°K. As indicated earlier, a higher effective electron temperature leads to lower densities and thus lower fluxes. Taking the above mentioned escape flux value and integrating it over the exobase (in effect the actual) surface of Europa gives an overall escape rate of about 4.4×10^{25} atoms sec^{-1}. The limited observational data base [*Kliore et al.*, 1997] clearly indicates that it is unrealistic to assume uniform ionospheric densities over Europa; nevertheless this estimate of the escape rate leads to a reasonable general estimate and can be compared to the most recently calculated atmospheric sputtering rate due to elastic collisions, estimated by *Saur et al.* [1998] to be 8.5×10^{26} O_2 molecules sec^{-1}. Thus hot oxygen escape is not likely to be a major atmospheric loss process.

We established that there is a significant hot oxygen atom population in the exosphere of Europa. The major constituent in the exosphere is most likely to be the neutral oxygen molecules. An extended sodium corona has been also observed at Europa [*Brown and Hill*, 1996] with densities somewhat less than the hot oxygen values calculated here. It is quite likely that a significant neutral hydrogen atom corona is also present with densities that exceed all of these constituents at the higher altitudes. At this time there is no information available on these hydrogen densities at Europa; at Ganymede, Lyman alpha measurements indicate the presence of neutral hydrogen with a density of 10^4 cm^{-3} at the surface, and a scale height of 2634 km [*Barth et al.*, 1997]. An extended heavy atomic and molecular corona has major implications on the interaction of Jupiter's magnetosphere with Europa. The Galileo magnetometer measurements [*Kivelson et al.*, 1998] appear to indicate the presence of such an extended mass-loading atmosphere. The specific effect(s) of such an extended exosphere can only be established by some detailed calculations. It has been shown for Mars that a hot oxygen corona, with densities significantly less than the hydrogen densities, is the dominant mass loading factor and plays an important role in the solar wind interaction with the planet [*Bauske et al.*, 1998]. A three-dimensional, multiscale, mass-loaded, MHD model, appropriate for studying the interaction of Jupiter's magnetosphere with Europa is available [*Kabin et al.*, 1997; Kabin et al., Interaction of Europa's atmosphere with Jupiter's magnetosphere; An MHD simulation, *J. Geophys. Res.*, submitted, 1998] and will soon be used to assess the importance of "heavy" atoms and molecules present in the exosphere.

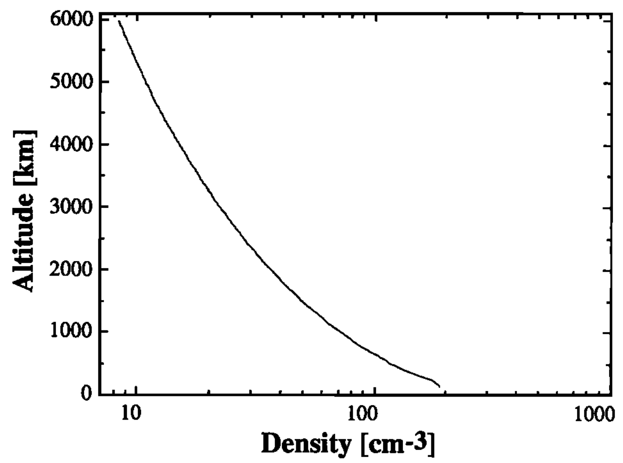

Figure 1. Calculated hot oxygen atom densities.

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References

Alge, E., N. G. Adams, and D. Smith, Measurements of the dissociative recombination coefficients of O_2^+, NO^+ and NH_4^+ in the temperature range 200-600 K, *J. Phys. B.*, *16*, No. 8, 1433-1444, 1983.

Banks, P. M., and G. Kockarts, *Aeronomy*, Academic, San Diego, Calif., 1973.

Barth, C. A., et al., Galileo ultraviolet spectrometer observations of atomic hydrogen in the atmosphere of Ganymede, *Geophys. Res. Lett.*, *24*, 2147-2150, 1997.

Bauske, R., et al., 3D multiscale mass loaded MHD simulations of the solar wind interaction with Venus and Mars, 32nd COSPAR Scientific Assembly, Nagoya, 1998; also to be published in *Adv. Space Res.*

Brown, M. E., and R. E. Hill, Discovery of an extended sodium atmosphere around Europa, *Nature*, *380*, 229-231, 1996.

Hall, D. T., D. F. Strobel, P. D. Feldman, M. A. McGrath, and H. A. Weaver, Detection of an oxygen atmosphere on Jupiter's moon Europa, *Nature*, *373*, 677-679, 1995.

Kabin, K., M. R. Combi, T. I. Gombosi, A. F. Nagy, D. L. DeZeeuw, and K. G. Powell, Interaction of Europa's atmosphere with Jupiter's magnetosphere; A 3D multiscale simulation, *Bull. Amer. Astron. Soc.* *29*, 985, 1997.

Kella, D., P. J. Johnson, H. B. Pedersen, L. Vejby-Christensen, and L. H. Andersen, The source of green light emission determined from a heavy-ion storage ring experiment, *Science*, *276*, 1530-1533, 1997.

Kivelson, M. G., et al., Induced or intrinsic fields in a periodically varying plasma environment, UCLA/IGPP Publication No. 5086, 1998.

Kliore, A. J., D. P. Hinson, F. M. Flasar, A. F. Nagy, and T. E. Cravens, The ionosphere of Europa from Galileo radio occultations, *Science, 277*, 355-358, 1997.

Mehr, F. J., and M. A. Biondi, Electron temperature dependence of recombination of O_2^+ and N_2^+ ions with electrons, *Phys. Rev., 181*, 264-270, 1969.

Nagy, A. F., and T. E. Cravens, Hot oxygen atoms in the upper atmospheres of Venus and Mars, *Geophys. Res. Lett., 15*, 433-435, 1988.

Nagy, A. F., J. Kim, and T. E. Cravens, Hot hydrogen and oxygen atoms in the upper atmospheres of Venus and Mars, *Ann. Geophysicae, 8*, 251-256, 1990.

Saur, J., D. F. Strobel, and F. M. Neubauer, Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere, *J. Geophys. Res., 103*, No. E9, 19,947-19,962, 1998.

Schreier, R., A. Eviatar, V. M. Vasyliunas, and J. D. Richardson, *J. Geophys. Res., 98*, 21,231-21,243, 1993.

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