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Europa's atmospheric neutral escape: Importance of symmetrical O_2 charge exchange

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ABSTRACT

We model the interaction of the jovian magnetospheric plasma with the atmosphere of Europa using a multi-species chemistry model where the atmospheric distributions of H_2 and O_2 are prescribed. The plasma flow is idealized as an incompressible flow around a conducting obstacle. We compute changes in plasma composition resulting from this interaction as well as the reaction rates integrated over the simulation domain for several upstream plasma conditions (ion density, ion temperature and flow velocity). We show that for all cases, the main atmospheric loss process is a cascade of symmetrical charge exchanges on O_2, which results in the ejection of neutrals. The production rate of ejected neutrals is about an order of magnitude larger than the production of ions. This conclusion is relevant to future missions to Europa that aim to detect fast neutrals. The neutral ejection resulting from this charge exchange creates an oxygen cloud around the orbit of the moon that is very extended radially but also very tenuous, and has not yet been directly detected.

1. Introduction

Europa, the second Galilean moon of Jupiter, has a radius $R_E = 1561$ km and orbits Jupiter at a distance = $9.4R_J$ (where R_J is Jupiter's radius = 71,492 km). Europa's orbit is embedded in a torus of plasma, which is mainly composed of multiply charged O and S ions corotating with Jupiter. These ions (average mass ~ 18.5 amu, average charge ~ 1.5, temperature ~ 100 eV, gyroradius ~ 8 km) impinge on Europa at a relative velocity ~ 100 km/s. The local torus electron density is $n_{el} \sim 200\ \mathrm{cm}^{-3}$. This population includes a thermal component at $T_{el} \sim 20$ eV and a small population (~5%) of hot electrons (~250 eV). The jovian magnetic field at Europa is ~370 nT. The plasma properties at Europa presented here are average values from Kivelson et al. (2004) but were shown be very variable in Bagenal et al. (2015), depending on the location of Europa in the torus but also depending on the time of the observations.

Europa's tenuous atmosphere has a surface pressure so low that the molecules seldom collide with each other (see reviews by Johnson et al., 2009; McGrath et al., 2009; Burger and Johnson, 2004; Burger et al., 2010; Coustenis et al., 2010). The atmosphere is thought to be produced largely by ion bombardment of its icy surface, though Roth et al. (2014a) recently suggest that there may also be a contribution from plumes. Ion sputtering produces H_2O molecules that fall back on the icy surface. But some of the water molecules are dissociated, initiating a chemical process call radiolysis that produces O_2, H_2, and other species. The light H_2 molecules escape Europa's gravity to form an extended corona. The heavier O_2 molecules have ballistic trajectories and form a bound O_2 atmosphere.

Between 1996 and 2000, the Galileo spacecraft made several flybys of Europa and the instruments on board measured the plasma and magnetic field properties. The local interaction was modeled by several authors along some of the Galileo flybys. Kabin et al. (1999) used an MHD model to simulate the E4 flybys assuming a prescribed induced field inside Europa. Schilling et al. (2008) developed an MHD code to address explicitly the magnetic induction in Europa's oceans. Lipatov et al. (2010) developed a hybrid code to model the E4 and E6 flybys.

The most comprehensive treatment to date of the plasma-neutral chemistry was by Saur et al. (1998) who modeled the plasma properties for the E4 flyby conditions. They developed a 3-D model under the assumption that the magnetic field is uniform and not perturbed by the interaction with Europa. They studied the source and sink of the molecular atmosphere and proposed their preferred O_2 atmospheric distribution (a vertical column = $5 \times 10^{14}\ \mathrm{cm}^{-2}$ and a scale height = 145 km) that was consistent with the atmospheric mass balance between surface sputtering and atmospheric loss, under the E4 plasma properties. We

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will use a similar distribution to define our "Standard" O_2 atmosphere in sensitivity experiments presented in Section 5.

The goal of this paper is to estimate the neutral loss rate of the atmosphere of Europa. We demonstrate that the interaction of the jovian plasma with the atmosphere is an important source of escaping O_2 neutrals. Previous models of Europa's atmosphere (Ip, 1996; Shematovich et al., 2005; Smyth and Marconi, 2006; Cassidy et al., 2009; Plainaki et al., 2010, 2012) compute the O_2 atmosphere loss by only considering the electron impact ionization and molecular dissociation processes. In this study, we claim that the atmospheric loss rate is larger than estimated by these authors because of a process that they ignore, which is a cascade of symmetrical charge exchanges between O_2^+ ions and neutral O_2 (hereafter called "Sym-chex"). Once an atmospheric O_2 is ionized by electron impact or photo-ionization, it is not immediately lost to the magnetosphere. The ion is first picked up by the flow and entrained through the atmosphere. It becomes the seed of a cascade of symmetrical charge exchanges with other atmospheric O_2 neutrals along the whole path of the flow through the atmosphere. Each charge exchange ejects a fast neutral until the ultimate ion is eventually convected out of the atmosphere. We show that the total production rate of ejected neutrals could be an order of magnitude larger than the production of ions. It seems to us that this important fact, although mentioned in Saur et al. (1998) for Europa and discussed in Saur et al. (1999) and Dols et al. (2008, 2012) for Io, has been overlooked by the community. With future missions focused on Europa, we reconsider this issue of atmospheric neutral losses at Europa. These neutral fluxes should be detectable by future missions to Europa with energetic neutral sensors (Milillo et al., 2013), such as the PEP instrument on the planned JUICE mission (Jupiter Icy moon Explorer) (Barabash et al., 2013). Furthermore, the ejection of molecular neutrals by symmetrical molecular charge exchange at low to fast velocity leads to interesting consequences: such neutral ejections from the atmosphere may form a large and tenuous oxygen cloud (molecular or atomic) spreading around the orbit of Europa. Moreover, fast neutrals could provide an additional source of atmospheric neutral molecules via sputtering, a process that has not been yet considered in the literature.

In this paper, we model the plasma interaction at Europa with a multi-species chemistry model that includes the most important physical chemistry reactions involving the atomic sulfur and oxygen ions as well as the electron populations present in the jovian torus as well as the molecular O_2 and H_2 ions produced in the atmosphere of Europa. A notable simplification of our approach is the description of the plasma flow around Europa as an incompressible flow around a conducting obstacle. A more accurate modeling of the flow is beyond the goal of this paper and we postpone to later work the comparison of the model results with the Galileo flyby observations. We will compare our results with the work of Saur et al. (1998). As their model includes only a single ion species, they defined an effective charge exchange cross section, which represents the interaction of both molecular and atomic ions with the O_2 atmosphere. The quantitative results of our chemistry approach are consistent with their results but as we model the multi-species chemistry, we are able to calculate the contribution of each ion species in the interaction process and demonstrate that a cascade of symmetrical charge exchange of O_2 is the main contributor to the neutral ejection from the atmosphere. We also present several simulations to illustrate the sensitivity of this molecular neutral loss with varying incoming plasma conditions as well as variation of the extension of the neutral O_2 corona of Europa.

In Section 2, we describe the different parts of our model and review the relevant literature: the atmospheric distribution of O_2 and H_2, the plasma flow around Europa, the physical chemistry reactions. In Section 3, we apply our model to the E4 Galileo flyby plasma condition and compare to Saur et al. (1998). In Section 4, we present a "Standard" case, where we apply the model to a typical torus plasma condition and a "Standard" O_2 atmospheric profile. In Section 5, we present sensitivity experiments where we investigate the variation of Europa's atmospheric neutral loss when we include, sequentially, an H_2 extended corona, a variation in the radial extent of the O_2 atmosphere, a variation of the torus plasma conditions, and a hot electron population. We summarize our result in Section 6.

2. The model

The concept of the multi-species chemistry modeling has already been presented in Dols et al. (2008, 2012) for Io: we follow a parcel of torus plasma of known composition and energy along prescribed flow lines around the object, in this case Europa. The parcel encounters a prescribed O_2 and H_2 atmosphere where ionization, charge exchange, recombination and molecular dissociation take place, changing the ion composition and the ion temperature of the parcel. In this chemical approach, we neglect the electro-dynamic interaction that perturbs the magnetic field around Europa. We also ignore the tilt of the background magnetic field as well as the presence of an induced magnetic field in the ocean of Europa. These simplifications do not alter significantly our conclusion about the importance of the Europa neutral loss by symmetrical charge exchange.

Our model is 2-D in the equatorial plane (XY) of Europa. The simulation box extends from $8R_E$ upstream to $8R_E$ downstream of Europa in the corotation direction (X), and from $-4R_E$ to $+4R_E$ in the jovian direction (Y). The composition of the plasma is sampled downstream of Europa in the equatorial plane along a hypothetical trajectory at $X = 1.5R_E$ to study the evolution of the plasma composition. The O_2 and H_2 neutral loss rates are then integrated over the whole 2-D simulation box, assuming an extension of the Europa atmosphere = $2R_E$ in the perpendicular direction (Z).

2.1. Prescribed atmosphere

The neutral atmosphere in our model is prescribed. The neutral loss processes considered here are assumed not to affect the neutral density. Atmospheric parameters are poorly constrained by existing observations so we consider a range of parameters from published models.

2.1.1. Standard atmosphere

For our standard case we use the O_2 atmosphere described by Saur et al. (1998). The atmosphere has an average vertical column density of 5×10^{14} cm^{-2}, similar to values reported by Hall et al. (1995, 1998), and has a large scale height = 150 km and is spherically symmetrical. The O_2 density near the surface for this model is 0.33×10^8 cm^{-3}. Describing the O_2 atmosphere with a single scale height and assuming a spherical symmetry is an oversimplification. As the neutral O_2 population is generated by radiolysis and thermalized with the surface, it is expected that the real vertical profile comprises a cold dense population with a hotter population at higher altitudes (Plainaki et al., 2012). Other local processes such as Joule and electron impact heating could vary the scale height with altitude. Moreover, asymmetries of the atmospheric distribution are expected because of the asymmetry of the insolation and direction of the incident plasma (Plainaki et al., 2013). The simplifications adopted here do not alter the salient point of this paper, which is the importance of the symmetrical charge exchange process during the local interaction at Europa. We postpone to future work a more detailed description of the atmosphere and the flow around Europa (see Section 2.2).