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Loss rates of Europa's tenuous atmosphere

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ABSTRACT

Loss processes in Europa's tenuous atmosphere are dominated by plasma–neutral interactions. Based on the updated data of the plasma conditions in the vicinity of Europa (Bagenal et al. 2015), we provide estimations of the atmosphere loss rates for the H_2O, O_2 and H_2 populations. Due to the high variability of the plasma proprieties, we perform our investigation for three sample plasma environment cases identified by Bagenal et al. as hot/low density, cold/high density, and an intermediate case. The role of charge-exchange interactions between atmospheric neutrals and three different plasma populations, i.e. magnetospheric, pickup, and ionospheric ions, is examined in detail. Our assumptions related to the pickup and to the ionospheric populations are based on the model by Sittler et al. (2013). We find that O_2–O_2^+ charge-exchange is the fastest loss process for the most abundant atmospheric species O_2, though this loss process has been neglected in previous atmospheric models. Using both the revised O_2 column density obtained from the EGEON model (Plainaki et al., 2013) and the current loss rate estimates, we find that the upper limit for the volume integrated loss rate due to O_2–O_2^+ charge exchange is in the range $(13–51)\times 10^{26}\ s^{-1}$, depending on the moon's orbital phase and illumination conditions. The results of the current study are relevant to the investigation of Europa's interaction with Jupiter's magnetospheric plasma.

1. Introduction

The tenuous atmosphere (often referred to as exosphere) of Jupiter's moon Europa has been known to comprise mainly the following populations: H_2O, released mainly through ion sputtering (Brown et al., 1982, Plainaki et al. 2010, 2012; Cassidy et al., 2013) and secondarily through sublimation (Shematovich et al., 2005); O_2 and H_2, both species produced through chemical reactions among different products of H_2O radiolytic decomposition (Johnson, 1990; Shematovich et al., 2005; Cassidy et al., 2010; Plainaki et al., 2010, 2012); and some minor species like Na and K (Brown and Hill, 1996; Brown, 2001; Leblanc et al., 2002, 2005) and H, O, HO_2, and H_2O_2 (Baragiola, 2003). A direct measurement of the main atmospheric species has not been performed yet since the limited available observations are just proxies of the bulk constituents (e.g. the OI UV emission can be a proxy for O_2). The discovery of an O_2 atmosphere was made by Hall et al. (1995,1998) using Hubble Space Telescope (HST) observations of far ultraviolet emission of atomic oxygen. The ratio of the two observed emission lines at 1304 Å and 1356 Å was used to identify dissociative excitation of O_2 as the origin of the emissions. Later, the observations of the Ultraviolet Imaging Spectrograph (UVIS) onboard Cassini confirmed the existence of a tenuous O_2 atmosphere during Cassini's flyby of Jupiter (Hansen et al., 2005). Recent observations with HST have revealed surpluses of hydrogen Lyman alpha and atomic oxygen emissions above the moon's southern hemisphere that have been interpreted as evidence of transient vapor water plumes (Roth et al., 2014). It is noted, however, that the plumes have not been detected after or confirmed at all, so the status is at the current moment unclear (Roth et al., 2014b).

The source processes responsible for the generation of the tenuous atmosphere of Europa as well as the chemistry between exospheric neutrals and plasma have been discussed many times in the past (see in Plainaki et al. (2012, 2013); Cassidy et al. (2010, 2013); Krupp et al. (2010); Dalton et al. (2010); Coustenis et al. (2010); Bagenal et al. (2004); Pappalardo et al. (2009)). In particular, plasma–neutral interactions have been mainly studied either

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on the basis of Voyager and Galileo flyby data (Kabin et al., 1999; Bagenal et al., 2004; Schilling et al., 2008; Lipatov et al., 2010) or through numerical (Saur et al., 1998) and Monte Carlo models (Shematovich et al., 2005; Smyth and Marconi, 2006; Plainaki et al., 2012). However, the lack of a sufficient series of in situ measurements able to: (a) further constrain the estimates obtained through the above mentioned studies and (b) determine the variability of the magnetospheric plasma properties around Europa, has significantly limited our knowledge of plasma–neutral interactions and the temporal and spatial variability of the atmosphere loss rates. On the other hand, our understanding of the tenuous atmosphere sources has been significantly expanded by the results of a series of related laboratory ice experiments (Brown et al., 1978; Baragiola, 2003; Teolis et al., 2005; Galli et al., 2015). Nevertheless, a thorough and detailed determination of the balance between atmosphere sources and losses is expected to come once new in situ data will be obtained (i.e. during the ESA/JUICE and the NASA/Europa missions).

In view of preparation for future missions to Europa, accurate estimates of the loss rates for the main constituents of the tenuous atmosphere of Europa, based on state-of-the art knowledge of plasma properties near the satellite as well as the latest laboratory derived cross sections for different plasma–neutral interactions, is of significant help. The scope of this paper is to provide detailed estimates of the loss rates, using updated plasma conditions calculated recently by Bagenal et al. (2015) based on the analysis of Galileo data. We provide a broad list of reactions, not discussed thoroughly in previous Monte Carlo modeling papers, and we estimate for the first time their impact on Europa's neutral environment for three sample plasma environment cases (hot and low density, cold and high density, and an intermediate case that in this paper is referred to as "medium"). All previous studies including estimates of loss rates were based: (a) on Voyager-1 data (e.g.: Sittler and Strobel, 1987) or (b) Cassini data (Delamere et al., 2005) or (c) on plasma properties information provided by the earlier Bagenal (1994) model (e.g.: Saur et al., 1998; Smyth and Marconi, 2006; Shematovich et al., 2005; Plainaki et al., 2012, 2013). We also include, for the first time, temporal variability of the loss rates due to the large variability in plasma properties. The tilt of Jupiter's magnetic field is another source of temporal variability as it brings Europa in and out of the dense plasma near Europa's centrifugal equator. The motivation for this work, therefore, is to provide an add-on to current knowledge, which can be used as a resource for the improvement of future plasma and atmosphere/exosphere models. Additionally, we investigate the role of different charge-exchange interactions between ionosphere/pickup ions and atmospheric neutrals, for all three dominant atmosphere species, namely water, oxygen and hydrogen. In previous studies (Shematovich et al., 2005; Smyth and Marconi, 2006) charge exchange processes were found to be of negligible importance. For completeness, we provide information also on photoreactions for both cases of a quiet and an active Sun. The paper is organized as follows: in Section 2 we provide loss rate estimates for Europa's tenuous atmosphere. In Section 3 we compare our results with those of previous calculations and discuss them in the context of future in situ measurements. Conclusions are given in Section 4.

2. Loss processes: rates and variability

Interactions of the tenuous atmosphere of Europa with Jupiter's magnetospheric plasma and, to a lesser extent, solar UV photons, lead to the ionization and/or dissociation of its constituents. Whereas such mechanisms result in the actual atmosphere loss, they provide also a supply of fresh ions and new atoms to the near-Europa space environment. Fresh ions can contribute to the further ionization of the neutral environment (Dols et al., 2016). Moreover the freshly dissociated molecules modify the composition of the tenuous atmosphere, creating inhomogeneities in the nominal neutral distribution around the moon. Interactions in the near-Europa space environment, therefore, result in both dynamical changes of the plasma composition and temperature and effective atmosphere loss.

2.1. Plasma–neutral interactions

Cross sections for plasma–neutral interactions are energy dependent and hence the respective reaction rates depend on the speed distribution of the plasma, as well as the densities of each reactant (Burger et al., 2010). Therefore, in order to address the role of the different loss mechanisms, the external plasma environment has to be considered first.

The plasma properties in the space environment in which Europa is embedded have been identified in detail in the past by the model of Bagenal (1994), which was based on Voyager-1 Ultraviolet Spectrometer (UVS) data (Shemansky, 1987; Bagenal et al., 1992) and Plasma Spectrometer (PLS) measurements in Jupiter's inner magnetosphere. According to this model the plasma electron population at Europa's orbit includes a core cold and a hot component that can be approximated by two Maxwellian distributions (at ~20 and ~250 eV, respectively). Moreover, the plasma properties were shown to have a variability depending on the location of Europa with respect to the Jupiter Plasma Sheet (JPS). In particular, due to the tilted (with respect to JPS) orbit of Europa, the plasma density falls off north/south of above/below the centrifugal equator with a scale height of ~ 1 R_J for 50–100 eV plasma (Kivelson et al., 2004). As Europa moves in its orbit, it effectively moves up and down the JPS and the density and temperature of the local plasma change remarkably. The Bagenal (1994) model predicted for the electron density at the orbit of Europa values of ~35–40 cm^{-3} off the equator and values of 80–110 cm^{-3} near it, depending on the strength of the equatorial current. Observed electron densities over Galileo flybys of Europa ranged from 18 cm^{-3} to 250 cm^{-3} (Gurnett et al., 1998; Kurth et al., 2001). Ion-mixing ratios in the vicinity of Europa were estimated by Delamere et al. (2005) on the basis of the Cassini Ultraviolet Imaging Spectrograph (UVIS) data (Steffl et al., 2004). We note that the earlier models based on analyses of Voyager UVS data had lower abundances of S^{2+} and higher abundances of O^{+} than the estimates of Steffl et al. (2004). Such differences between model outputs may be due to differences in the analysis techniques, different coverage of the UV spectrum, or actual changes in the torus conditions at the time of the measurements. Recently, Bagenal et al. (2015) analyzed the available Galileo PLS and Plasma Wave Spectrometer (PWS) data to derive electron density, azimuthal speed and ion temperature in the vicinity of Europa's orbit (away from Europa itself, though). They found that the flow speed has a narrow distribution around a median value that is equal to ~83% of the corotation speed. Based on the observed temporal variability of the plasma, Bagenal et al. (2015) provided three cases of plasma conditions: (a) Low density, high temperature; (b) Medium conditions of density and temperature; and (c) high density, low temperature. We use these updated plasma electron and ion conditions in the near-Europa space environment, as given in Bagenal et al. (2015), to estimate the loss rates of the tenuous atmosphere. These are provided in Table 1.

Whereas the available in-situ measurements guide the construction of plasma torus models in the near Europa space environment, the plasma properties in the near the surface regions are currently known with less certainty and they are mainly provided by models. 3D hybrid models (e.g. Lipatov et al., 2010, 2013) or 3D MHD models (Schilling et al., 2007, 2008; Rubin et al., 2015) of the plasma interaction provide some insights into the near the surface plasma environment. Although (a) strong evidence for the existence

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