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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

Table 1
Plasma properties in the near-Europa space environment as estimated by Bagenal et al. (2015) on the basis of **the available** Galileo data. The ion composition is based on the physical chemistry model by Delamere et al. (2005).

Plasma condition:		**(1) Low/hot**	**(2) Medium**	**(3) High/cold**	**Note**
$T(S^{+})$ (eV)	S^{+} temperature	500	130	70	
$T(S^{2+})$ (eV)	S^{2+} temperature	250	65	40	
$T(S^{3+})$ (eV)	S^{3+} temperature	170	45	25	
$T(O^{+})$ (eV)	O^{+} temperature	500	130	70	
$T(O^{2+})$ (eV)	O^{2+} temperature	340	90	50	
$T(H^{+})$ (eV)	H^{+} temperature	70	17	10	
T_i (eV)	Ion temperature	340	88	48	From the Galileo/PLS instrument
V (km/s)	Flow speed	123	98	76	From the Galileo/PLS instrument
T_e cold (eV)	Electron temperature (cold component)	30	20	10	
T_e hot (eV)	Electron temperature (hot component)	1200	300	200	
N_e (cm^{-3})	(cold) Electron density	63	158	290	From the Galileo/PWS instrument
N_e (hot) / N_e	Hot to cold electron density ratio	0.1	0.05	0.02	
$N(S^{+})/N_e$	S^{+} composition	0.02	0.02	0.02	Delamere et al. (2005)
$N(S^{2+})/N_e$	S^{2+} composition	0.14	0.14	0.14	Delamere et al. (2005)
$N(S^{3+})/N_e$	S^{3+} composition	0.04	0.04	0.04	Delamere et al. (2005)
$N(O^{+})/N_e$	O^{+} composition	0.3	0.3	0.3	Delamere et al. (2005)
$N(O^{2+})/N_e$	O^{2+} composition	0.08	0.08	0.08	Delamere et al. (2005)
$N(H^{+})/N_e$	H^{+} composition	0.12	0.12	0.12	Delamere et al. (2005)
$\langle A_i \rangle$	Assumed mass of the dominant heavy ion species (amu)	18	18	18	Delamere et al. (2005), Bagenal et al. (2015)
$\langle Z_i \rangle$	Assumed charge of the dominant ion species (q)	1.5	1.5	1.5	Delamere et al. (2005), Bagenal et al. (2015)
B (nT)	Background magnetic field	480	450	423	

of an ionosphere has been provided through the Galileo Radio Science observations (Kliore et al., 1997) and (b) so far substantial progress in modeling has been made, there are still significant uncertainties considering the specific characteristics (e.g. height and thickness) of the ionospheric layer between the impinging magnetospheric ions and the moon's surface. Indeed, Sittler et al. (2013) discussed the complexity of inferring Europa's ionospheric scale height from Galileo Radio Science observations and concluded that the inferred electron density should be interpreted combining also the knowledge obtained through a global interaction model (e.g. Lipatov et al., 2010). Moreover, these authors noted that several plasma modeling efforts of the past could not resolve the problem of determining the characteristics of the ionopause due to either the modeling technique itself (for example the MHD models by Schilling et al. (2007, 2008) assumed guiding-center approximation for the ions) or due to low model-resolution (for example, equal to ~150 km in the model by Lipatov et al. (2010).

Understanding the characteristics of Europa's ionosphere is of significant importance in order to determine atmospheric loss rates. In general, in a planetary (or lunar) atmosphere, below the ionopause, i.e. the transitional region between ions of magnetospheric origin and ionospheric ions, the external plasma does not penetrate, the convective electric field of the external flow is near zero and the gyroradius of the local ions is essentially zero. At altitudes above the ionopause the pick-up ions dominate, the plasma flow is non-zero and the convective electric field will be relatively large. If the thickness of the ionopause is large with respect to its height then the ionopause does not occur and the external plasma flow can penetrate down to the moon's surface. Recent simulations by Sittler et al. (2013) showed that at Europa the plasma flow can extend down near the surface when the O_2 column density is low enough. In particular, they showed that for a column density equal to $\sim 5 \times 10^{14}$ O_2 cm^{-2} the plasma flow stopped essentially at the altitude of 40 km defined as the height of the occurrence of the ionopause. Moreover, the model by Sittler et al. (2013) provides the density profile of pick up ions of different species for altitudes up to 200 km from the surface (see in Sittler et al. (2013), Fig. 9). The ionosphere and pick up ion properties provided by Sittler et al. (2013) are used in the current paper in order to estimate the atmosphere loss rates.

Based on the above description, the interactions between plasma and Europa's tenuous atmosphere refer either to electron–neutral or to ion–neutral collisions. In the latter case, the interactions refer (potentially) to three ion populations, namely the ions in the plasma torus (with origin from Io), dominating at altitudes $> \sim 200$ km; the ionosphere ions, originating from the ionization of the sputtered neutral tenuous atmosphere, dominating at altitudes $< \sim 40$ km; and the pickup ions created from atmospheric neutrals outside of the ionosphere, where newly-created ions are accelerated by the corotation electric field. The term "potential" refers to the uncertainty for the existence of an ionospheric layer at Europa. In the current paper, we estimate the loss rates corresponding to electron and ion interactions with the neutral tenuous atmosphere for the three plasma torus conditions given in Table 1 and the main ionospheric and pickup ion populations provided in Sittler et al. (2013). In the current paper we consider only the main constituents of Europa's tenuous atmosphere, namely H_2O, O_2 and H_2. Although the expected ice irradiation processes at Europa do not exclude the existence of some other less abundant atmosphere species, such as OH and H (Watanabe et al., 2000) or H_2O_2 and HO_2 (Kimmel et al., 1994; Orlando and Kimmel, 1997) and other minor components of the surface, laboratory measurements of ice irradiation experiments have shown that water molecules dominate the total release yield at lower temperatures (<120 K) and molecular oxygen and hydrogen at higher (>120 K) temperatures (Johnson and Kanik, 2001).

2.1.1. *Electron–neutral interactions*

Plasma electrons impacting the tenuous atmosphere of Europa can dissociate and/or ionize its various constituents. The dissociation (or ionization) rate ν due to electron impact processes is computed by

$$\nu_e = \kappa(V_e) N_e \tag{1}$$

where N_e is the electron density and κ is the rate coefficient of the reaction (in cm^3 s^{-1}), determined from the cross section of the reaction and the velocity distribution function $f(V_e)$, where V_e is the velocity of the electrons measured relative to the neutrals. For electron impact processes, the plasma flow speeds (also called bulk velocities) can be ignored since the electron thermal speeds are much larger. For example, cold 20 eV electrons (Medium case in Table 1) have velocities of $\sim 2.7 \times 10^3$ km/s which are much larger than the measured flow speed in the near-Europa space, equal to ~98 km/s (Bagenal et al., 2015). Therefore, for a thermalized (Maxwellian) electron population, the rate coefficient is a

Table 2
Electron impact reactions rates for different plasma conditions.

Reaction		**ν (10^{-6} s^{-1})**						**Note**
		Low/hot		**Medium**		**High/Cold**		
		Cold	**Hot** [(a)]	**Cold**	**Hot**	**Cold**	**Hot**	
1.	$H_2O+e \rightarrow OH+H+e$	3.0		3.31	1.28	0.92	0.96	[1,2]
2.	$H_2O+e \rightarrow H_2O^++2e$	1.88	0.58			0.18[(b)]	0.61	[2]
3.	$H_2O+e \rightarrow OH^++H+2e$	0.37	0.19	1.94	0.84		0.2	[2]
4.	$H_2O+e \rightarrow OH+H^++2e$	0.99	0.15	0.069	0.28		0.19	[2]
5.	$H_2O+e \rightarrow H_2+O^++2e$	0.0085	0.026	0.013	0.26		0.039	[2,3]
6.	$O_2+e \rightarrow O+O+e$	1.43		0.0014	0.05	1.57[(b)]	0.16[(c)]	[4]
7.	$O_2+e \rightarrow O_2^++O+e$	1.5	0.79	2.58		0.082[(b)]	0.76[(c)]	[5]
8.	$O_2+e \rightarrow O^++O+e$	0.28	0.42	1.18	1.1		0.47[(c)]	[5]
9.	$H_2+e \rightarrow H+H+e$	1.2421		0.091	0.66	3.55		[6]
10.	$H_2+e \rightarrow H_2^++e$	1.482	0.27	3.55		1.32	0.45	[7]
11.	$H_2+e \rightarrow H^++H+e$	0.019	0.016	1.32	0.45	0.024	0.036	[7]

Reaction 1. Cross sections measured over an energy range from threshold to 300 eV [1].
Reaction 2, 3, 4, 5. Reaction cross section measured from threshold to 1000 eV [2, 3].
Reaction 6. Cross sections measured over an energy range from 13.5 eV to 198.5 eV [4].
Reaction 8. Cross section corresponding to an electron temperature of 10 eV is below the threshold [5].
Reaction 9. Cross sections measured over an energy range from 9 eV to 80 eV [6].
Reaction 10, 11. Cross sections measured over an energy range from threshold to 1000 eV [7].
Table References: [1] Harb et al. (2001a,b); [2] Itikawa and Mason (2005); [3] Shirai et al. (2001); [4] Cosby (1993); [5] Itikawa (2009); [6] Yoon et al. (2008); [7] Straub et al. (1996).

[(a)] The cross section for the hot electron population are reported for an energy equal to 1000 eV (instead of 1200 eV) because cross sections for higher electron temperature are not reported in [2,3].

[(b)] The cross section are reported for an energy equal to 13.5 eV

[(c)] The cross section are reported for an energy equal to 198 eV

function of the electron temperature:

$$\kappa(T_e) = \int V_e f(V_e)\sigma(V_e)dV_e \tag{2}$$

where $f(V_e)$ is the Maxwellian velocity distribution function of the electron population and σ is the experimentally determined cross section of the reaction. In order to estimate κ we approximately consider the mean electron velocity $<V_e> = \frac{2}{\sqrt{\pi}}\sqrt{\frac{2k_bT_e}{m_e}}$ of a Maxwellian distribution function. Our results for different plasma electron populations are presented in Table 2.

2.1.2. Ion–neutral interactions

Ion–neutral reactions refer to collisions between plasma ions and neutral species. The charge-exchange (also called “charge transfer”) is a collisional process that takes place during the interaction between a relatively fast (energetic) ion and a cold neutral. During this process the fast ion and the cold neutral exchange their charge hence an energetic neutral atom (ENA) and a cold ion are being formed. If the projectile and the target particles are of the same species, charge exchange is a symmetric (resonant) process (Hasted and Hussain, 1964) and the newly created ENA retains approximately both the energy of the colliding energetic ion and its direction (e.g. Milillo et al., 2005). In case of different species, either a non-resonant process (e.g. proton projectile and He target) or an "accidental resonance" in ionization energies (e.g. O^+ projectile and H target) can occur (Fite, 1963). The "accidental resonance", by which it is meant that the energy defect is almost zero but the two ions are not chemically identical, permits charge exchange to proceed rapidly in thermal energies (Banks and Kockarts, 1973). If the mean free path of the newly created ENAs is long enough, such an ENA can transport information out of the generation region, thus allowing remote sensing of the interaction process (e.g. Roelof et al., 1985; Roelof, 1987; Daglis and Livi, 1995; Orsini and Milillo, 1999; Barabash et al., 2001; Milillo et al., 2001; Orsini et al., 2001).

Charge-exchange rates are also determined by Eqs. (1) and (2) substituting the electron density and velocity, with the ion density (N_i) and velocity relative to the neutrals (V_i), respectively. Because ions are more massive than electrons, the relative bulk motion between the ions and neutrals is significant hence it needs to be taken into account when calculating the respective reaction cross section. The charge-exchange rate coefficient is given by:

$$\kappa(V_i) = \int V_i f(V_i)\sigma(V_i)dV_i \tag{3}$$

where $V_i = V - V_{orb}$, with V_{orb} being the orbital velocity of Europa, equal to 14 km/s, and V being the flow velocity of the plasma as derived from the Galileo PLS measurements (Bagenal et al., 2015). We note that if the thermal temperature is large then both the thermal (random) motions of the ions and the bulk motion of the plasma relative to the neutral gas must be considered. Such is the case of plasma being slowed as flowing through satellite exospheres or the Enceladus plume (Burger et al., 2010). Johnson et al. (2006) showed that the presence of H_3O^+ in the Saturnian plasma implied reactions between neutral and ionized water molecules at low relative velocities because the cross section for H_3O^+ production is large for speeds below ~10 km/s (Lishawa et al. 1990). For the Europa case, the random thermal ion velocities estimated by Bagenal et al. (2015) are in general lower than the flow velocity hence in the current study we neglect thermal motion. Future in-situ measurements of course will provide more detailed information on the plasma properties in the near-surface environment of Europa, allowing a more accurate evaluation of the rates of the plasma–neutral interactions.

In our loss rate estimates due to the interactions between the plasma torus ions and the neutrals (see Table 3a), we take into account only the S^{++} and O^+ ions, since they are the dominant species of the sub-corotating plasma, with densities equal to 15% and 20% of the electron density, as inferred from UV observation in Steffl et al. (2004), consistent with the model of Delamere et al. (2005). We underline that the low energy plasma composition was not measured directly by Galileo but it was inferred through the spectra and Mach numbers of the measured flows (Sittler et al., 2013). Indeed these measurements could not distinguish O^+ from S^{++} hence the relative abundances for these species are currently known only through remote observations plasma Io torus that do not include Europa's orbit. The complete composition of the plasma in the near-Europa space environment is presented in Table 1. We note that in the model of Delamere (2005) the proton density ($\sim$12% of the electron density) is derived as additional ion charge to match electron density and to satisfy charge neutrality. Since the H^+ composition is not a direct measurement, in the current study we do not estimate rates corresponding to plasma neutral reactions involving H^+.

Table 3a

Plasma flow charge exchange reactions rates given for reactions between S^{++} and O^+ ions and O_2, H_2 and H_2O neutrals. The ion velocity is equal to V–V_{orb}, where V_{orb} is the orbital velocity of Europa (equal to 14 km/s) and V is the flow velocity of the plasma as derived from the Galileo PLS measurements (Bagenal et al. 2015). The S^{++} and O^+ ion densities used to calculate the reaction rates are based on the physical chemistry model by Delamere et al. (2005), see Table 1.

	Low/hot	Medium	High/cold	Note
$\boldsymbol{V_{ions}}$ **(km/s)**	109	84	62	[1]
$\boldsymbol{N(S^{++})}$ **(cm^{-3})**	9	22	41	[2]
$\boldsymbol{N(O^{+})}$ **(cm^{-3})**	19	47	87	[2]
Reaction	**ν (10^{-6} s^{-1})**	**ν (10^{-6} s^{-1})**	**ν (10^{-6} s^{-1})**	
1.$S^{++} + O_2 \rightarrow S^+ + O_2^+$	0.15	0.28	0.38	[3]
2.$O^+ + O_2 \rightarrow O + O_2^+$	0.27	0.51	0.7	[3]
3.$S^{++} + H_2 \rightarrow S^+ + H_2^+$	0.092	0.32	0.42	Copy of the below
4.$O^+ + H_2 \rightarrow O + H_2^+$	0.092	0.32	0.42	[4]
5.$S^{++} + H_2O \rightarrow S^+ + H_2O^+$				
6.$O^+ + H_2O \rightarrow O + H_2O^+$		0.7	0.11	[5]

Reaction 3. The cross section is not available hence the value of the cross section of the reaction below was used (as Dols et al.,2016).
Reaction 5. Cross section value not found in literature.
Reaction 6. Cross section studied in the energy range **from** 1 to 400 eV.
Table references: [1] Bagenal et al. (2015)**;** [2] Delamere et al. (2005); [3] McGrath and Johnson (1989); [4] Tawara et al. (1985); [5] Turner and Rutherford (1968).

Regarding the loss rate estimates corresponding to the interactions between the ionospheric ions and the atmospheric neutrals, we attempt to provide an upper limit of the respective charge-exchange reactions considering the O_2^+, H_2O^+, and H_2^+ ionosphere densities at the height of the ionopause (where they maximize). Considering the interactions between pick-up ions and the atmosphere, in the current paper we provide estimates for altitudes >200 km, since the region between the height of 200 km and the ionopause is a transition region where the density of the pick-up ions is highly variable (see Sittler et al. (2013), Fig. 9). For the pick-up ions at the altitude of 200 km we assume a relative speed equal to the one of the plasma torus (see Table 1). We underline that our estimated loss rates due to pick-up ion interactions are consistent with the overall plasma neutrality. Note that Delamere et al. (2005) estimated that the addition of pickup O^+ ions and O_2^+ ions to the torus increases the net temperature from 130 eV and 100 eV to 300 eV and 200 eV respectively; the modification they bring to the plasma torus composition is minor. For the ionospheric ions, dominating at altitudes <40 km, we assume a velocity equal to $\sim$10 km/s as given by Sittler et al. (2013). Our results are presented in Table 3b. Although we did not perform any detailed calculations corresponding to the transition region between the ionopause and the altitude at which the plasma torus dominates (assumed to be equal to $\sim$200 km, as in Sittler et al. (2013)), we expect that the respective loss rates will vary between the values provided in Table 3a and b.

2.2. Photoreactions

Photoreaction rates are given at 1 AU by Huebner et al. (1992). These rates are inversely proportional to the distance of Europa from

Table 3b

Pick up and ionosphere charge exchange reactions rates given for reactions between O_2^+, H_2^+ and H_2O^+ ions and O_2, H_2 and H_2O neutrals. We assume for pick up ions a relative speed equal to the one of the plasma torus. The pick up ion density is provided by Sittler et al. (2013, Fig. 9) and it is equal to $\sim$10 cm^{-3} for the three ions species (O_2^+, H_2^+, H_2O^+), valid for the different plasma condition cases. The ionosphere ion velocity (10 km/s) and the ionosphere ion density are provided by Sittler et al. (2013). We assume an ion density equal to 10,000, 50 and 25 cm^{-3} for O_2^+, H_2^+, H_2O^+ ions respectively.

	Pick-up ions			Ionosphere	Note
	Low/hot	Medium	High/cold		
$\boldsymbol{V_{ions}}$ **(km/s)**	109	84	62	10	[1] pick up ions, [2] ionosphere ions
$\boldsymbol{N(O_2^{+})}$ **(cm^{-3})**	10	10	10	10,000	[2]
$\boldsymbol{N(H_2^{+})}$ **(cm^{-3})**	10	10	10	50	[2]
$\boldsymbol{N(H_2O^{+})}$ **(cm^{-3})**	10	10	10	25	[2]
Reaction	**ν (10^{-6} s^{-1})**	**ν (10^{-6} s^{-1})**	**ν (10^{-6} s^{-1})**	**ν (10^{-6} s^{-}1)**	
1.$O_2^+ + O_2 \rightarrow O_2 + O_2^+$		0.05	0.04	15	[3]
2.$H_2^+ + O_2 \rightarrow H_2 + O_2^+$	0.027	0.027	0.027	1.35	[4]
3.$H_2O^+ + O_2 \rightarrow H_2O + O_2^+$	0.002	0.002	0.002	0.005	[5]
4.$O_2^+ + H_2 \rightarrow O_2 + H_2^+$	0.066	0.034	0.019		[6,7]
5.$H_2^+ + H_2 \rightarrow H_2 + H_2^+$	0.0082	0.067	0.054	0.12	[8]
6.$H_2O^+ + H_2 \rightarrow H_2O + H_2^+$					
7.$O_2^+ + H_2O \rightarrow O_2 + H_2O^+$					
8.$H_2^+ + H_2O \rightarrow H_2 + H_2O^+$	0.44	0.42	0.36		[9]
9.$H_2O^+ + H_2O \rightarrow H_2O + H_3O^+$				0.025	[10]

Reaction 1. Cross section measured for energy up to 1000 eV [3].
Reaction 2, 3. The reaction rate coefficients for references [4,5] are published for a fixed gas temperature or a limited range of temperatures. These values are equal to 2.7×10^{-9} and 0.2×10^{-9}, which are reported from [4] and [5] respectively.
Reaction 4. Cross section measured from 100 eV [6,7].
Reaction 6, 7. Values not found in literature
Reaction 8. Cross section measured for incident ion energy range 30–500 eV.
Reaction 9. Cross section measured for energy up to 60 eV.
Table references: [1] Bagenal et al. (2015); [2] Sittler et al. (2013); [3] Benyoucef and Yousfi (2014); [4] Kim and Huntress (1975); [5] Fehsenfeld et al. (1967); [6] Irvine and Latimer (1997); [7] Hasan and Gray (2007); [8] Vance and Bailey (1966); [9] Coplan and Ogilvie (1970); [10] Lishawa et al. (1990).

Table 4
Photorections rates for H_2O, O_2 and H_2 from Huebner et al. (1992).

	Photo-reaction	**ν (10^{-6} s^{-1})**
1.	$H_2O+h\nu\rightarrow H+OH$	0.38–0.65
2.	$H_2O+h\nu\rightarrow H_2+O(^1D)$	0.022–0.055
3.	$H_2O+h\nu\rightarrow H+H+O$	0.028–0.71
4.	$H_2O+h\nu\rightarrow H_2O^++e$	0.012–0.031
5.	$H_2O+h\nu\rightarrow OH^++H+e$	0.0021–0.0056
6.	$H_2O+h\nu\rightarrow OH+H^++e$	0.00048–0.0015
7.	$H_2O+h\nu\rightarrow H_2+O^++e$	0.00022–0.00082
7.	$O_2+h\nu\rightarrow O(^3P)+O(^3P)$	0.0052–0.0082
8.	$O_2+h\nu\rightarrow O(^3P)+O(^1D)$	0.15–0.24
9.	$O_2+ h\nu\rightarrow O\ (^1S)+O(^1S)$	0.0015–0.0035
10.	$O_2+h\nu\rightarrow O_2^++e$	0.017–0.044
11.	$O_2+ h\nu\rightarrow O+O^++e$	0.004–0.013
12.	$H_2+h\nu\rightarrow H(^1S)+H(^1S)(^1S)$	0.0018–0.004
13.	$H_2+h\nu\ \rightarrow H(^1S)+H(2s,2p)$	0.0013–0.003
14.	$H_2+h\nu\rightarrow H_2^++e$	0.002–0.004
15.	$H_2+h\nu\rightarrow H+H^++e$	0.00035–0.0011

the Sun squared. The values listed in Table 4 are for quiet and active Sun at Europa's orbit (5.2 AU) for H_2O, O_2 and H_2 Photo-reactions.

For completeness, we mention that the contribution coming from fresh photoelectrons that have enough energy to dissociate and ionize the neutrals. We estimate that the rate resulting from this secondary process is about 10–30% of the photoreaction rate. This is a standard approximation used in the aeronomic studies, that was checked and validated in the accurate calculations of the photo and photoelectron rates for different planetary atmospheres (see, for example, Hubert et al., 2012 and Ionov et al., 2014).

3. Discussion

3.1. Overall results on the H_2O, H_2, and O_2 loss rates

For the H_2O constituent of the atmosphere we find that the dominant loss is due to electron impact dissociation. As shown in Table 2, such process is expected to have an efficiency that varies with the assumed plasma conditions (i.e. density and temperature). We note that such plasma conditions (taken from the Bagenal et al., 2015) depend on both the location of Europa with respect to the JPS and on the epoch of the Galileo observations on which the plasma model was based. Maximum loss is expected for the orbital phases of median plasma conditions (Case (2) in Table 2) and it is estimated to be equal to $3.31\times10^{-6}\ s^{-1}$. Production of minor species H and OH is favored during these phases. We note that the cold plasma electron population is the main responsible for the H_2O atmosphere loss.

For H_2 we find that the dominant loss process is electron impact ionization (leading to the production of ${H_2}^+$) when Europa is under median plasma conditions, and electron impact dissociation when Europa is found under conditions of high plasma density and low plasma temperature (Case (3) in Table 2). Both processes have a rate equal to $3.55\times10^{-6}\ s^{-1}$. The dissociation process populates the tenuous atmosphere with H atoms that, given their low mass, can easily escape the moon's gravity and make part of Europa's neutral cloud (gravitationally bounded to Jupiter).

For O_2 we find that charge-exchange reactions between the ionospheric ${O_2}^+$ and exospheric O_2 molecules have the highest rates with respect to all other loss process. In particular, we find that the ${O_2}^+$–O_2 reaction rate, equal to $\sim15\times10^{-6}\ s^{-1}$, is by a factor of $\sim$6 and $\sim$10 higher than the ones corresponding to electron impact ionization (medium case in Table 2) and electron impact dissociation (High/cold case in Table 2) processes, respectively. Of course this result is also due to the actual assumption on the reactant's density, which in this study was considered as in Sittler et al. (2013). Nevertheless, the domination of the ${O_2}^+$–O_2 charge exchange over all other loss processes is in agreement with Dols et al. (2016), who used different assumptions to estimate the importance of this process as well as a multi-species chemistry model. As in case of H_2O and H_2 tenuous atmospheres the efficiency of the electron impact processes depends strongly on the plasma conditions. In particular, the electron impact ionization loss rate varies by a factor up to $\sim$3.4 and the dissociation rate by a factor up to $\sim$3.1 among the three considered cases of plasma conditions. Although these processes are not the ones determining the actual loss of atmospheric molecules, their rates can be used in order to roughly estimate the production of ionosphere ${O_2}^+$ and atomic oxygen. Information on such intermediate products of the plasma–neutral interactions, however minor, can be of use during the interpretation of remote sensing measurements of Europa's tenuous atmosphere (as for example: the ultraviolet line emission of atomic oxygen).

3.2. Volume-integrated O_2 loss rates using the EGEON model

In order to calculate the volume integrated neutral loss rates we use the O_2 tenuous atmosphere described by the EGEON model (Plainaki et al., 2012, 2013), including the revised release yields described in Plainaki et al. (2015). We consider two different configurations between Jupiter, Europa and the Sun: Conf.1, subsolar point coincides with the leading hemisphere apex and Conf. 3, subsolar point coincides with the trailing hemisphere apex[1]. For the Conf. 1 case the spatially averaged O_2 column density given by the revised EGEON model is equal to $2.7\times10^{18}\ m^{-2}$ whereas for the Conf. 3 case it is equal to $1.1\times10^{19}\ m^{-2}$. As shown in Table 3b the charge exchange reaction rates due to the pick up and ionosphere processes differ by almost three orders of magnitude. Moreover, the O_2 atmospheric density falls off by more than 2 orders of magnitude after the first 100 s of kms (the low-altitude scale height of the EGEON model is equal to $\sim$20 km (see Milillo et al., 2015)). This means that the dominant charge-exchange loss takes place at low altitudes and is due to the slow, i.e. 10 km/s, ${O_2}^+$ (ionospheric) population. Therefore in our calculation we use the respected reaction rate.

The O_2 volume integrated loss rates due to the dominant loss mechanisms (these are charge-exchange, electron impact ionization and electron impact dissociation, in order of efficiency) are presented in Table 5. For comparison, in Table 5, we also present the results obtained through other studies. The respective volume integrated loss rates calculated through different models are also presented. We note that in our estimates, the volume-integrated loss rates are proportional to the neutral column density and they depend on some more or less free parameters (e.g. the energy of the ionospheric particles). Given the uncertainty in the determination of such parameters, the derived estimations can be used to validate the whole approach of the loss calculations to first order, but cannot be considered as an independent estimation of the absolute loss of the atmosphere.

Table 5 shows that the ionspheric plasma–neutral interaction is the most important agent for O_2 depletion. However, we note that the estimated rates corresponding to charge-exchange presented in Table 5 do not represent a net atmosphere loss as a single charge-exchange reaction results both in the loss of a relatively cold O_2 atmospheric molecule (via charging) and the production of an energetic O_2 molecule; the latter will leave the Europan gravity field only if its velocity is larger than the escape velocity and if its

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[1] Note that in the current paper the same nomenclature as in Plainaki et al. (2013) has been considered for the different configurations, between Jupiter, Europa and the Sun.

Table 5
Volume integrated O_2 loss rates calculated through different models.

Model O_2 loss process	Smyth and Marconi (2006) **(10^{26} s^{-1})**	Shematovich et al. (2005) **(10^{26} s − 1)**	Saur et al. (1998) **(10^{26} s^{-1})**	Dols et al., 2016) **(10^{26} s − 1)**	**this work** **(10^{26} s − 1)**
Ionization		4.6[a],[b]; 5.3[c],[b]	1.2	4.8	2.2– 8.8[d],[e]
Dissociation		0.039		3	1.3–5.3 [d],[f]
Charge-exchange	2.7	0.88[a]; 0.014[c]	7.3	29.31	13–51[d],[g],[h]

[a] This value corresponds to Model D in Shematovich et al. (2005).

[b] This value includes ionization, charge-exchange and sweeping effects.

[c] This value corresponds to Model B in Shematovich et al. (2005)

[d] The lower and upper limits in the rates estimated in this work correspond to *Conf.1* and *Conf.3* cases, respectively, for the considered O_2 exosphere (see text).

[e] Plasma conditions corresponding to Case (2) were considered (see Table 1)

[f] Plasma conditions corresponding to Case (3) were considered (see Table 1)

[g] The charge-exchange volume integrated rates in this work were estimated for the reaction $O_2^+ + O_2 \rightarrow O_2 + O_2^+$ which is the most effective one according to Table 3b. The ionosphere $O_2{}^+$ density given by Sittler et al. (2013) was considered in the calculation.

[h] Assuming that at least half of the fresh energetic O_2 molecules produced through charge-exchange have velocities directions favoring escape, the net loss due to this process is expected to have values equal to 1/2 of the ones presented here (see also text). In this context, the rates reported here are upper limit values of the atmosphere loss due to charge-exchange.

trajectory does not intersect the surface. We can assume that the first condition is satisfied almost always since the $O_2{}^+$ velocity (in the current study assumed to be equal to ~10 km/s, following Sittler et al. (2013)) is larger than escape velocity (equal to ~2.0 km/s) and since this collisional process can be considered elastic, though the incoming ion will lose some momentum during the collision. The second condition, however, is not satisfied for every reaction. Therefore, the net loss rate due to charge exchange will depend on the balance between the gain due to the freshly generated energetic O_2 molecules (i.e those that do not escape Europa's gravity field) and the loss due to the freshly ionized O_2. Due to this fact, the estimates presented in Table 5 are upper limits for the loss of the O_2 atmosphere due to charge exchange. Recently, Dols et al. (2016) modeled symmetrical charge-exchange cascades between $O_2{}^+$ and O_2 and showed that the total production rate of ejected neutrals could be even an order of magnitude larger than the production of ions. In the current calculation, we make the rough assumption that at least half of the fresh energetic O_2 molecules produced through charge-exchange have velocities directions favoring escape. In this case, we deduce that the expected loss of the exospheric O_2 due to charge-exchange has values equal to 1/2 of the ones presented in Table 5 hence ranging between $6.5 \times 10^{26}\,s^{-1}$and $26 \times 10^{26}\,s^{-1}$. We note that the charge-exchange process in any case will lead to a modification of the energy distribution of the exospheric population since it favors the loss of cold populations and the gain of energetic ones. An accurate estimate of the spatial and temporal dependence of the tenuous atmosphere loss as well as the determination of the O_2 energy distribution function resulting from the consideration of all loss processes, requires a detailed analytical or Direct Simulation Monte Carlo model (DSMC) and goes beyond the scope of this paper.

As shown in Table 5, the O_2 volume integrated loss rates estimated in this study are by more than one order of magnitude larger than those calculated by Smyth and Marconi (2006) and by Shematovich et al. (2005). On the other hand, our results are consistent with those by Dols et al, (2016). This is because this study, as well as the study by Dols et al, (2016), includes the charge exchange loss process between the high density ionospheric $O_2{}^+$ population and the atmospheric O_2. Small differences between our estimated rates and those by Dols et al. (2016) are due to the atmospheric model used as a basis for the calculation. Dols et al. used the atmosphere column densities of Smyth and Marconi (2006) whereas we used the ones of EGEON, in Plainaki et al. (2013), revised due to yield corrections (see Milillo et al., 2015; Plainaki et al., 2015). On the other hand, Saur et al. (1998) estimated the neutral losses due to both ionization and charge exchange. In order to make a comparison of the results presented in this paper and those in Saur et al. (1998), some clarifications regarding the vocabulary and calculation methods are necessary. Regarding ionization, what was actually calculated by Saur et al. was the flux of the ionized neutrals hitting the surface of Europa or being convected out of Europa's atmosphere. Such a process is referred to as "pick up loss" in that paper. Regarding charge exchange, Saur et al. (1998) computed a flux of ions out of the exobase generated after a collision of an ion with a neutral. We note that in that calculation the authors considered only the charge exchange cross section, whereas the respective loss process was referred to as “atmospheric sputtering”[2]. On the basis of the above, it is reasonable to compare quantitatively our ionization and charge exchange results with the pick up loss and atmospheric sputtering results, respectively, presented in Table 2 in the Saur et al. (1998) paper. We find that the volume-integrated ionization loss rate calculated by Saur et al. is consistent with our results. In addition, our net charge-exchange volume integrated loss rate (ranging from $6.5 \times 10^{26}\,s^{-1}$to $26 \times 10^{26}\,s^{-1}$) is similar to the one of Saur, when considering the tenuous atmosphere configuration Conf.1 (i.e. leading hemisphere is the illuminated one) and it is ~3 times larger in the Conf.3 atmosphere configuration (i.e. trailing hemisphere is the illuminated one). Since the loss rate is proportional to the atmospheric density, the difference between our results and those in Saur et al. (1998) can be explained by differences in the assumed neutral density and cross sections. For the Conf.1 atmosphere configuration the EGEON model gives a column density of $2.7 \times 10^{18}\,m^{-2}$, similar to the one assumed by Saur et al. (equal to $5 \times 10^{18}\,m^{-2}$) hence the averaged volume integrated loss rates are very similar. For the Conf.3 atmosphere configuration the EGEON model gives a column density equal to $11 \times 10^{18}\,m^{-2}$ which is 2.2 times higher than the one assumed by Saur et al. We note that such a dense atmosphere is the result of the effectiveness of the radiolysis process leading to a major surface release (and hence atmosphere generation) when the trailing hemisphere of the moon is illuminated, as shown in Plainaki et al. (2013). Nevertheless, the obtained rates (see Table 5) are not strictly proportional since energy-dependent cross sections were considered in this study. Saur et al. (1998) assumed an effective charge exchange cross section value corresponding to an ion velocity of 60 km/s, equal to $2.6 \times 10^{-19}\,m^2$. Moreover, on the basis of the method used in our paper, our estimates (Table 5, 6th column) depend on the column density of the considered neutral model (rather than its atmospheric scale height) as well as on the actual rate corresponding to the loss process. Other estimates (see Table 5) were based on different methods (e.g. numerical methods as in Dols et al., 2016). It is, however, very difficult to test principle dependencies of those

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[2] Note that according to Johnson et al. (1994) the term "atmospheric sputtering" **refers** to the combination of many processes rather than a single one.

estimations and to understand the extent to which the (volume integrated) results in the past works depended either on the neutral (plasma) models themselves (e.g. scale height variation) or on the considered efficiencies of the loss processes. To achieve such a distinction (that would permit a more in depth comparison between different studies) detailed knowledge on each past model is necessary. Such an investigation, however challenging, goes beyond the scope of the current paper.

3.3. Add-on to current knowledge

The main conclusion of the current study is that one of the dominant loss processes of Europa's tenuous atmosphere is charge-exchange between the tenuous O_2 atmosphere and its own ionospheric ions. However, this rather unexpected result should be treated with caution due to uncertainties in the determination of the energy distribution function and density of the pickup ions due to limited in-situ measurements. It is known that electron densities up to 10^4 cm^{-3} were measured very close to the moon's surface, however, the determination of the dominant ion species is still open. ${O_2}^+$ could be the main ion, but in the very near-surface layer the situation is rather complicated for the following two reasons: (1) ${O_2}^+$ can be lost via its dissociative recombination with the ionospheric (thermal) electrons; and (2) ionization chemistry in the $O_2+H_2+H_2O$ mixtures results in the domination of the ${O_2}^+$, O_2H^+ and H_3O^+ ions (Larsson et al., 2012). Although H_2 and H_2O are minor species, nevertheless they should change the ion composition near surface. Such reactions could reduce our above estimated charge-exchange rates up to one order of magnitude.

The physics of plasma-moon interactions in the Jupiter system is one of the major interests of the international scientific community, especially in view of the upcoming JUICE mission (Grasset et al., 2013). The understanding of the spatial and temporal variability of Europa's neutral environment as well as of the implications of its interactions with the moon's internal ocean, require detailed knowledge of the neutral-plasma interactions. The related existing observations, obtained with HST (Hall et al., 1998; McGrath et al., 2004; Saur et al., 2011) and to a lesser extent in situ (Kliore et al., 1997; Kurth et al., 2001; Hansen et al., 2005), have provided important constraints for determining the atmospheric source and loss rates. However, due to (a) the lack of a direct measurement of the main atmospheric species; (b) the existence of several atmospheric models based on very different approaches (e.g. assuming either the collisional (e.g. Shematovich et al., 2005; Smyth and Marconi, 2006) or the collisionless (Plainaki et al., 2012) approximation); (c) the existence of several plasma interaction models (e.g. Saur et al., 1998; Sittler et al., 2013; Dols et al., 2016); (d) recent debates on the nature of Europa's neutral and plasma environments (see paper by Shemansky et al. (2014)), our current understanding of Europa's plasma-neutral interactions is still fragmentary. In view of the future JUICE mission observations, the need for an overall revision of the source and loss mechanisms for the atmosphere of Europa is urgent. In this context, this paper provides a rough estimation of the efficiency of the dominant interactions at Europa that can be used as a starting point for future modeling studies of the moon's environment. Such models could be used as basic tools for planning the future JUICE observations and, later, for interpreting the actual atmosphere and plasma measurements.

4. Conclusions

In the current study the loss rates of the main components of Europa's tenuous atmosphere (O_2, H_2O, H_2) were estimated on the basis of energy-dependent reaction cross sections found in literature and, for the first time, updated plasma conditions obtained from the recent state-of-the-art analysis by Bagenal et al. (2015). We performed calculations for electron impact dissociation and ionization processes, for charge-exchange (considering separately three plasma populations: plasma torus, pick up and ionospheric ions) and for photo processes (for both quiet and active solar activity). For the dominant (in the near-surface regions) O_2 species, the volume integrated loss rates were estimated, using the revised (for the surface release yields) O_2 exosphere described by the EGEON model, for two different configurations between Europa, Jupiter and the Sun (i.e. subsolar point coincides with the leading hemisphere apex and subsolar point coincides with the trailing hemisphere apex) (Plainaki et al., 2013). The results of the current paper can be summarized as follows:

- For both H_2O and H_2 tenuous atmospheres, the loss rates depend on the highly variable plasma conditions. The cold plasma electron population is primarily responsible for H_2O and H_2 loss, in particular maximum loss is expected under median plasma conditions and median or high plasma conditions for H_2O and H_2, respectively.
- For the O_2 tenuous atmosphere, we find the O_2–${O_2}^+$ charge-exchange process may have a dominant role in the atmospheric loss, in agreement with Dols et al. (2016) but contrary to what has been suggested by previous atmospheric models. Using the revised O_2 column density based on the EGEON model (Plainaki et al., 2013), we estimate that the upper limit of the O_2–${O_2}^+$ charge exchange rate is in the range $(13–51)\times10^{26}$ s^{-1}, depending on the configuration between Europa, Jupiter and the Sun.

We underline that the volume-integrated O_2 loss rates presented in this paper are proportional to the neutral column density considered, depending on parameters that at the current moment cannot be determined with certainty (e.g. the energy spectrum of ionospheric particles in the first atmospheric layers). In the current estimates, therefore, information based on both mission and laboratory data as well as theoretical models of the past have been used as an input. As a consequence, there are two limitations to be taken into account when referring to the O_2 volume integrated loss estimated in the current paper: (1) whereas the current results can be used to validate the whole approach of the O_2 loss calculations to first order, they cannot be considered as an independent estimation of the absolute loss of the atmosphere; (2) the column density of the considered neutral model (rather than its atmospheric scale height) as well as the actual process rate determine the calculated global loss of O_2. The latter means that the role of the details (dynamics, energy distribution) of the neutral atmosphere itself has not been taken into account during the calculation of the loss. Moreover, it is pointed out that the calculation of an altitude-independent loss rate is indeed a rough estimation since the plasma neutral collision rate can have a spatial variability. Nevertheless, given the absence of an extended series of plasma data in the near-surface environment of Europa, the uncertainty in the determination of the various parameters is an intrinsic problem that diminishes the value of any attempt to go into much detail in the atmosphere loss estimations, and in particular in their dependence on altitude. However, a future attempt in this direction could be challenging since in any case it would provide feedback for the evaluation of how the basic principles of each atmosphere model determine the actual loss.

The estimates provided in this paper, however rough, are a first attempt to investigate the dependence of the reaction rates corresponding to plasma-neutral interactions on the plasma conditions at Europa. Temporal variability of the atmospheric loss rates, due to the large variability in plasma properties, has been intrinsically considered in our study. The results presented in Tables 2–4 provide an add-on to current knowledge and a useful feedback for further theoretical or mission-related studies. In view of future missions to the Galilean satellites, namely JUICE and NASA mission to Europa, the current estimates could be useful for the planning of observation strategies and, later, for the interpretation of the observations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.pss.2016.01.009.

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