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Europa's ice-related atmosphere: The sputter contribution

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A B S T R A C T

Europa, Jupiter's innermost icy satellite, is embedded well within Jupiter's magnetospheric plasma, an intense flux of ions and electrons that approximately co-rotate with Jupiter. The plasma can be thought of as consisting of two populations: The cold, thermal plasma containing charged particles with energies ranging from 1 eV to 1 keV, and the hot, energetic plasma containing charged particles with energies ranging from 10 keV to 100 MeV. When the charged particles interact with Europa's surface, they not only chemically and physically alter the icy surface, but also liberate material from the surface through a process called sputtering, which in turn forms a tenuous atmosphere.

In this paper we calculate the sputter contribution to the atmosphere by modeling the formation of Europa's ice-sputtered atmosphere ab initio. We consider the species H, H_2, O, OH, H_2O, O_2, HO_2, H_2O_2, and O_3, all of which are related to the water–ice surface. Whereas the ice sputter yields of H2O, H2, and O2 have been well established, the ice sputter yields (and the resulting density profiles) of H, O, OH, HO_2 and O_3 are small and largely unknown. As model input we use available plasma ion and electron energy spectra as well as available water-ice sputter yields. Based on first principles, i.e., without applying any scaling to observed data, we calculate atmospheric densities ab initio.

Our results match available observational data and previously published modeling efforts well. Europa's exosphere is dominated by thermally accommodated O_2 close to the surface (below a few 100 km), and the much lighter H_2 molecules at higher altitudes. The water-ice related species that stick to the surface (freeze out) are liberated by cold and hot plasma sputtering in about equal amounts. In addition, in the case of H_2, O_2, and H_2O_2, electrons contribute almost as significantly to the sputter yield as ions do.

1. Introduction

Europa's orbit is located at an average distance of 9.38 R_J from Jupiter (where R_J is Jupiter's radius, or 71,400 km) and nearly coincides with Jupiter's equatorial plane. The moon's orbit thus lies well inside the jovian magnetopause, which is typically located at 60–100 R_J (Joy et al., 2002), and at the outer edge of the Io plasma torus. Jupiter's magnetospheric plasma approximately co-rotates with Jupiter, lagging only marginally behind Jupiter's rotation period of ∼10 h, thus traveling at an average speed of ∼90 km/s at Europa's orbital distance. Europa's orbital speed of ∼14 km/s is substantially lower than the azimuthal plasma velocity, resulting in the plasma flowing over the moon from it's trailing hemisphere and sweeping ahead of it in its orbital motion with a relative speed of ∼76 km/s. Whereas the main part of the Jovian plasma consists of this cold, thermal plasma, there is a second population, termed the hot, energetic plasma. This plasma has been accelerated to energies surpassing 10 keV, and, while it is quite sparse, it contains most of the overall energy flux.

As the Jovian plasma encounters Europa's surface, two important processes are induced: radiolysis and sputtering. Radiolysis is the dissociation of molecules into fragments by ionizing radiation inside the ice. Since the resulting fragments are mostly radicals they are chemically reactive, and will recombine to form new, more stable, species in the ice. The second process, sputtering, is the ejection of particles from a solid surface due to its bombardment by energetic particles. The number of ejected particles depends on the plasma flux, the plasma energy, the plasma composition, the plasma charge state, the plasma incidence angle, and the surface temperature.

In the theoretical formulation, the sputter yield is a function of an ion's stopping power, i.e., the energy per length that is deposited as the ion passes through a solid (Betz and Wehner, 1983). At higher energies, the stopping power linearly increases with velocity up to ∼300 keV/nuc, above which it starts to decrease again. Several sputter experiments on ice have been conducted to determine the sputter yield of water ice (the number of ejected H_2O molecules per incident ion) for various ion species at various ener-

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gies. See Cassidy et al. (2013), Fig. 3, for a compilation of available water sputter yield data and theory. Recently, first sputter yield measurements for electrons sputtering water ice were presented by Galli et al. (2017).

In this paper we calculate ab initio the contributions to the exosphere by sputtering of water ice by cold and hot plasma ions and electrons. Available observations of Europa's water ice related atmosphere are presented in Section 2. The Monte Carlo model, including plasma parameters and sputter yields, are presented in Section 3. The results of our Monte Carlo simulation are presented in Section 4, and a comparison with available observations and previous models is given in Section 5. Section 6, the conclusion section, completes this paper.

2. Available observations

Very little is known about the chemical composition of Europa's atmosphere from observations (see recent review by McGrath et al., 2009). The only presently confirmed exospheric constituents consist of its main component O and O_2, the alkali metals Na and K, H_2O (in form of plumes), and, detected most recently, a H corona. Whereas O_2 and H_2O was not directly observed, their presence was inferred from O and H observations. The following subsections give an overview of present-day available observations of Europa's water ice related atmosphere.

2.1. O and O_2

Hall et al. (1995) detected O I 1304 Å and O I 1356 Å air-glow emissions in Europa's exosphere using the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) during six consecutive spacecraft orbits in June 1994. Their measurements yield an O I 1356 Å–1304 Å atmospheric emission ratio of 1.9, implying electron dissociation excitation of O_2 as the responsible emission process, since this is the only process known to produce a brighter 1356 Å than 1304 Å line. Through atmospheric modeling the authors derive an O_2 column density of $N_C(O_2) = (1.5 \pm 0.5) \cdot 10^{15}$ cm^{-2} and a 2.5 σ upper limit for the O column density of $N_C(O) < 2 \cdot 10^{14}$ cm^{-2}.

Three years later, Hall et al. (1998) presented two more sets of HST/GHRS observations of Europa's exosphere made in June 1996 and July 1996. Complete analysis of HST/HGRS observations yield air-glow emission ratios between 1.3 and 2.2. Assuming both a uniform atmosphere and a spatially uniform electron impact excitation rate, the authors derive O_2 column densities of $N_C(O_2) = (2.4–14) \cdot 10^{14}$ cm^{-2} and 3 σ upper limits for the O column density of $N_C(O) < (1.6–3.4) \cdot 10^{13}$ cm^{-2}.

In 1999, McGrath et al. (2004) obtained 9 images of Europa's trailing hemisphere from the Space Telescope Imaging Spectrograph (STIS) on board HST. Surprisingly, the O I atomic emission 1356 Å peaks within the disk and not at the limb of the satellite, as would be expected from plasma interaction with an optically thin atmosphere. In addition, the images include a brighter region on the antijovian hemisphere, i.e., the emission is spatially inhomogeneous, probably due to the surface not being icy to the same degree everywhere.

Hansen et al. (2005) observed the O multiplet of lines with Cassini's Ultra-Violet Imaging Spectrograph (UVIS) on two different dates in January 2001. Their measurements are best fit by a bound, near-surface O_2 atmosphere with a scale height of $\sim$200 km and an O atmosphere consisting of a loosely bound component showing the spectral character of a point source and a diffuse component, which overfills one pixel ($\sim$7 R_E, where R_E is equal to Europa's radius of 1569 km). From their measurements the authors derive atomic and molecular oxygen densities and column densities, and an O/(O + O_2) ratio of 0.02.

Four more sets of UV observations of Europa were taken in spring 2007 by the HST Wide-Field Planetary Camera 2 (WFPC2), by the HST Advanced Camera for Surveys (ACS), and by New Horizons' Alice UV imaging spectrograph (Retherford et al. (2007). See also McGrath et al. (2009) and references therein). While the WFPC2 images do not reveal any measurable atmospheric emissions, the ACS images contain emissions at 1304 Å and 1356 Å on the subjovian hemisphere. Unfortunately, the latter images are difficult to interpret due to detector dark noise and due to the uncertainty of Europa's location within the images. The Alice measurements also cover emissions at 1304 Å and 1356 Å, confirming the value of $\sim$2 for the 1356 Å to 1304 Å ratio, again suggesting an O_2 dominated atmosphere.

In 2011 Saur et al. (2011) presented five previously unpublished HST/ACS measurements taken in June 2008. While the authors did not find any asymmetry in the atmospheric emission with respect to the sub-Jovian/anti-Jovian side, they did find a surplus of emission near 90° west longitude. Making similar assumptions as Hall et al. (1995), Saur et al. (2011) derive a lower limit of the O_2 column density of $N_C(O_2) > (6–10) \cdot 10^{14}$ cm^{-2}. These measurements are generally compatible with previous observations, being slightly smaller than the fluxes obtained with HST/STIS by McGrath et al. (2004, 2009) but in the range or slightly larger than previous HST/GHRS observations.

Most recently, Roth et al. (2016) presented a comprehensive set of HST observations of Europa's far ultraviolet oxygen aurora. The measured O I 1356Å to 1304Å flux ratio of 1.5–2.8, with a mean of 2.0, agrees well with previously published ratios, supporting the conclusion that Europa's bound atmosphere is dominated by O_2. Generally, the oxygen ratio decreases with increasing distance from the surface, with O_2 prevailing over O up to $\sim$900 km. The authors divided the data into three regions (near-surface up to 1.25 R_E, high altitude from 1.25 R_E to 1.5 R_E, and corona from 1.5 R_E to 1.6 R_E) and derive O/O_2 mixing ratios of 0.01–0.06, 0.13–0.15, and 0.27–0.35, for the three altitude regions. Considering various aspects of the variable plasma environment and the atmospheric distribution, the authors derive O_2 column densities of $N_C(O_2) = (3–6) \cdot 10^{14}$ cm^{-2}. The variable mixing ratio is suggesting largely different scale heights for the O and O_2 exospheric components.

2.2. H

Recently, Roth et al. (2017) reported on the first observations of an atomic hydrogen corona extending up to several moon radii above the limb of Europa. The observations were taken by STIS onboard the HST on six occasions between December 2014 and March 2015. The observations agree well with a radially escaping H corona with maximum densities at the surface of $N(H) = (1.5–2.25) \cdot 10^3$ cm^{-3}, with an average of $N(H) = 1.8 \cdot 10^3$ cm^{-3}, and a line-of-sight $1/r$ profile. The fitted densities vary by $\pm$20% for the six observations, which exceeds the obtained uncertainties. The authors thus concluded that an intrinsic variability of the H corona must exist.

2.3. H_2O

In 2014 Roth et al. (2014) reported on statistically significant coincident excess of hydrogen Lyman-α and oxygen 1304 Å emissions above Europa's southern hemisphere measured by HST/STIS. These highly variable emission excesses suggest a local atmospheric H_2O enhancement, most probably a 200 ± 100 km high water plume located on the anti-Jovian southern hemisphere. The authors derive average H_2O and O_2 column densities using measured cross sections for electron-impact dissociative excitation and standard plasma parameters for Europa. Their analysis yields an O_2 column density of $N_C(O_2) \sim 5 \cdot 10^{15}$ cm^{-2} and a H_2O column density of