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Towards a global unified model of Europa's tenuous atmosphere

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1 Towards a global unified model of 2 Europa's tenuous atmosphere

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12 June 2017

Abstract

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Despite the numerous modeling efforts of the past, our knowledge on the radiation-induced physical and chemical processes in Europa's tenuous atmosphere and on the exchange of material between the moon's surface and Jupiter's magnetosphere remains limited. In lack of an adequate number of in situ observations, the existence of a wide variety of models based on different scenarios and considerations has resulted in a fragmentary understanding of the interactions of the magnetospheric ion population with both the moon's surface and neutral gas envelope. Models show large discrepancy in the source and loss rates of the different constituents as well as in the determination of the spatial distribution of the atmosphere and its variation with time. The existence of several models based on very different approaches highlights the need of a detailed comparison among them with the final goal of developing a unified model of Europa's tenuous atmosphere. The availability to the science community of such a model could be of particular interest in view of the planning of the future mission observations (e.g., ESA's JUICE mission, and NASA's Europa Clipper mission). We review the existing models of Europa's tenuous atmosphere and discuss each of their derived characteristics of the neutral environment. We also discuss discrepancies among different models and the assumptions of the plasma environment in the vicinity of Europa. A summary of the existing observations of both the neutral and the plasma environments at Europa is also presented. The characteristics of a global unified model of the tenuous atmosphere are, then, discussed. Finally we identify needed future experimental work in laboratories and propose some suitable observation strategies for upcoming missions.

Keywords: Europa, exosphere, plasma sheet, sputtering

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108 **1. Introduction**

109 Jupiter's moon Europa possesses a tenuous atmosphere, generated predominantly

110 through the interaction of the plasma environment with the moon's icy surface and

111 characterized by a quasi-collisionless gas (Burger and Johnson 2004; Burger et al.

112 2010; Coustenis et al. 2010; Johnson et al. 2008; McGrath et al. 2009). There is

113 general consensus that this atmosphere is generated, predominantly, through ion

114 sputtering of the moon's icy surface upon its bombardment by magnetospheric

115 energetic ions, including O^{n+} , S^{n+} , H^+ with energies from ~10s of keV to several MeV

116 (Ip et al. 1998; Paranicas et al. 2002; Plainaki et al. 2012) and plasma ions with

117 thermal energies of ~ 100 eV (Ip 1996; Bagenal et al. 2015; Cassidy et al. 2013;
118 Eviatar et al. 1985). Some species in the surface and the atmosphere are the result of
119 radiolysis. Water is expected to be the dominant sputtered species, whereas significant
120 amounts of O_2 and H_2 are released from the surface through a two-step process: water
121 molecules dissociate generating different molecules (e.g. OH, H, H_2 , O) which further
122 react chemically to produce, mainly, O_2 and H_2 (Bahr et al. 2001). Moreover,
123 sublimation of water ice in the illuminated hemisphere may result in a locally denser
124 atmosphere (e.g. Smyth and Marconi 2006). Recently, Roth et al. (2014b) suggested
125 that transient water plumes may provide additional material to the atmosphere.
126 Importantly, the morphology of the related UV-photon emission could not be
127 interpreted without some a priori assumptions on the atmosphere and plasma electron
128 spatial distributions derived from previous Galileo and Voyager mission
129 measurements. Photon-stimulated desorption of water-ice might also provide some
130 atmospheric particle contribution, although estimations based on laboratory data show
131 that this mechanism, in general, is not the dominant one (Plainaki et al. 2010).
132 However, increased UV photon fluxes illuminating the icy surface during periods of
133 intense solar activity (i.e., during solar flares) may result in an increased water release
134 from the surface. Meteoroid impact vaporization by high-speed interplanetary dust
135 particles is another possible atmospheric source (Cooper et al. 2001; Koschny and
136 Grün 2001; Schultz 1996).

137 Based on current knowledge, molecular oxygen is likely the most abundant
138 species in Europa's atmosphere because it does not stick to the surface (like H_2O
139 does), nor does it easily escape the moon's gravity (like H_2 does) (Johnson et al.
140 2008). The available Hubble Space Telescope (HST) observations (Hall et al. 1995;
141 McGrath et al. 2009; Roth et al. 2016) of UV emissions from O atoms were reported
142 to be consistent with the concept of an atmosphere dominated by O_2 . Cassini/UVIS
143 instrument measurements of more extended UV oxygen emissions are diagnostic of
144 escaping oxygen atoms (Hansen et al. 2005). Although the generation mechanisms of
145 atmospheric O_2 have been discussed many times in the past, there is still a
146 considerable uncertainty in the calculation of the atmosphere source/loss rates and the
147 respective density scale heights. For example, the production of Europa's atmosphere
148 and its variation in space and time may be very sensitive to the deflection of thermal

149 ions by the interaction currents – a major feed-back mechanism (Bagenal et al. 2015;
150 Rubin et al. 2015).

151 The existence of a wide variety of models based on different scenarios (e.g.
152 assuming either the collisional (Shematovich et al. 2005; Smyth and Marconi 2006) or
153 the collisionless (Cassidy et al. 2007; Plainaki et al. 2012) approximation) and
154 different considerations (e.g. spatially uniform (or not) source/loss rates) has resulted
155 in our understanding of Europa's neutral gas environment still being incomplete. In
156 view of the planning of future observations of Europa's atmosphere, the need for an
157 overall revision for the determination of a largely accepted unified model of this
158 environment becomes necessary.

159 Europa's exosphere, the uppermost region of the atmosphere, is spatially
160 confined only by its lower boundary, the exobase, which is defined as the altitude,
161 h_{exo} , at which the mean free path of a molecule, $\lambda(h_{exo}) = (n(h) \cdot \sigma)^{-1}$, is equal to
162 the scale height, $H(h_{exo}) = k_B T(h_{exo}) / mg(h_{exo})$ (thermal gas case). Since h_{exo} is
163 different for different atmospheric species, it is deduced that the exobase is an
164 extended region rather than a thin layer located at a single altitude. Equivalently to the
165 above definition, Europa's exobase is the region where the Knudsen number is equal
166 to ~ 1 , $Kn = \lambda(h) / H(h) \sim 1$, whereas below the exobase it is $Kn < 1$. The particle
167 motion in the tenuous atmosphere of Europa can be described, in general, through the
168 Boltzmann equation of kinetic theory, which is valid for the whole range of Kn .
169 Contrary to other solar system bodies with dense atmospheres, the region between the
170 moon's surface and the exobase at Europa is characterized by a Knudsen number
171 ranging between 0.1 and 1 for O_2 (Figure 1). In this region, the atmospheric molecules
172 have mean free paths of significant length to lead to local energy distributions not
173 being in thermal equilibrium. Due to the relatively high Kn values, this region can be
174 considered as an extended boundary (or Knudsen) layer, where the few collisions are
175 not enough to create thermodynamic equilibrium of the molecules, in contrast to a
176 collision-dominated region where a hydrodynamics regime is valid. This boundary
177 layer (with a width of about a few mean free paths) is of particular interest because it
178 can be considered as an extension of Europa's surface to the actual lower atmospheric
179 boundary and, therefore, an indicator of the surface composition and chemistry. The
180 particle motion in the extended Knudsen layer can be described through Direct
181 Simulation Monte Carlo (DSMC) models (e.g., Shematovich et al. 2005; Smyth and

182 Marconi 2006), where the solution of the Boltzmann equation for suprathermal atoms
183 and molecules is achieved through the use of Monte Carlo algorithms. In the
184 exospheric region, i.e., $Kn > 1$, a free molecular dynamics regime is valid and
185 collisionless numerical Monte Carlo models can be applied (e.g., Cassidy et al. 2007;
186 Plainaki et al. 2012; Wurz et al. 2014). Analytical models, where the atmosphere
187 density profile is approximated by an exponential form with either given scale
188 height(s) (e.g. Johnson, 1990; Milillo et al. 2016), or depletion length scale (see Saur
189 et al. 1998) are also available.

190 To distinguish regions of validity of the existing atmospheric models and to
191 attempt to search for convergence among them, it is fundamental to answer the
192 following question: at what altitude is Europa's exobase located and how thick is the
193 Knudsen boundary layer? Such information is fundamental for defining the different
194 regimes of molecular dynamics and for determining the efficiency of the different
195 plasma-neutral interactions. To answer such a question, in the absence of pertaining in
196 situ observations, only modeling, based on the available remote/in situ observations,
197 and laboratory measurements can be made. In the following sections we present the
198 complexity of the different assumptions, given the large number of unknown
199 environment parameters at Europa. We briefly present the problems related to the
200 definition of the structure of Europa's atmosphere, and we perform an in depth
201 comparison of existent atmospheric models. Specifically, we present a summary of
202 the available UV and VIS observations of Europa's atmosphere (Section 2.1), of the
203 plasma, energetic ions and magnetic field observations (Section 2.2), and of the torus
204 of Energetic Neutral Atoms (Section 2.3). In Section 3 we present the current state of
205 modeling of Europa's environment. In Section 3.1 we compare different plasma and
206 MHD models. In Section 3.2 we focus in the environmental modeling and we discuss
207 both the different modeling techniques and their implementation and we perform a
208 detailed comparison among them. Based on this comparison, we define in Section 3.3
209 the characteristics of a global unified model of Europa's atmosphere and in Section
210 3.4 we assess possible future lab-experimental work required to constrain the model.
211 In Section 4, in view of future missions to Europa, we suggest some observation
212 strategies that could be useful for the determination of the atmosphere generation
213 mechanism. Finally, in Section 5 we present the conclusions of the current work.

214 **2. Review of the available observations of Europa's neutral** 215 **and plasma environment**

216

217 **2.1. Summary of the available UV and VIS observations of Europa's** 218 **atmosphere**

219 Europa's neutral gas environment can so far be directly observed only through atomic
220 emissions or absorption, which have been detected from oxygen (O), sodium (Na),
221 potassium (K) and hydrogen (H). Other than at the neighboring moon Io where
222 several molecular atmospheric species such as SO₂, SO, NaCl and other species have
223 been measured at various wavelengths (e.g., Lellouch et al. 1996; Spencer et al.
224 2005), no molecules have yet been directly measured in Europa's more tenuous gas
225 environment. In the case of the detected far-ultraviolet O emissions, the measured
226 relative brightness of the optically allowed transition at 1304 Å and the semi-
227 forbidden transition at 1356 Å unambiguously identify dissociative excitation of O₂
228 from electron impact as a source mechanism. Hence, these observations provide
229 indirect evidence for O₂ in the atmosphere. The presence of a variety of other species
230 is also inferred indirectly, including H₂, H₂O, SO₂, and Cl.

231 We will first describe the available far-ultraviolet measurements that provide
232 by far the most information on the bulk atmosphere to date and are thus the most
233 important benchmark for the validation of atmosphere modeling efforts. Thereafter,
234 we describe the observations of trace species including some results on modeling
235 efforts to interpret these measurements.

236 ***2.1.1 Ultraviolet observations of Europa's oxygen atmosphere***

237 A comprehensive overview of observations of Europa's atmosphere until 2008 was
238 provided by McGrath et al. (2009). Their Table 1 summarizes numerous details of the
239 atmosphere-related observations and the respective publications. Since then, three
240 Hubble Space Telescope (HST) campaigns have been performed with multiple
241 imaging observations by the Space Telescope Imaging Spectrograph (STIS) between
242 November 2012 and April 2015 (Roth et al. 2016). Principally confirming the results
243 and interpretations detailed in McGrath et al. (2009), this HST dataset exceeds the

244 previous data in accuracy of the measured emissions, in the coverage of Europa's
245 longitudes and orbital positions, and often also in spatial resolution.

246 The first unambiguous detection of Europa's atmosphere (see Figure 2) was
247 achieved through far-ultraviolet observations by the HST Goddard High Resolution
248 Spectrograph (GHRS) (Hall et al. 1995). The spectrum revealed oxygen emissions,
249 which exceed the solar oxygen lines that are reflected from the surface of Europa and
250 which hence originate from Europa's neutral gas environment. Like this first
251 spectrum from 1994 (Hall et al. 1995), two follow-up observations (Hall et al. 1998)
252 consistently measured brighter oxygen emissions from the semi-forbidden oxygen
253 doublet OI ($^5S^0 - ^3P$) 1356 Å than from the optically allowed oxygen multiplet OI ($^3S^0$
254 $- ^3P$) 1304 Å.

255 After elimination of all emissions from sources other than Europa like the
256 sometimes bright scattered light from the geocorona, there are several general
257 processes contributing to the observed oxygen signal from Europa:

- 258 1) Solar emission lines and continuum photons reflected from the surface
- 259 2) Resonance fluorescence scattering of solar lines by atoms in the atmosphere
- 260 3) Electron impact excitation of O atoms or dissociative excitation of oxygen
261 bearing molecules such as O₂, H₂O, or CO₂, to produce excited O atoms.

262 At far-ultraviolet wavelengths the surface albedo and continuum solar incident flux
263 are more than an order of magnitude lower than at visible wavelengths leading to a
264 very faint signal of light reflected off the surface. This is ideal when searching for
265 faint atmospheric emissions. Only at the hydrogen Lyman- α line is the solar flux
266 higher, generating a brighter surface-reflection signal despite the low FUV albedo of
267 1-2%. The procedure to determine and eliminate the surface-reflection contributions
268 (1) is to adjust a solar spectrum to the measured brightness in a wavelength range
269 where no atmospheric emissions are expected. In the case of the GHRS spectra, the
270 singly ionized carbon emission line at 1335 Å is used to calibrate the solar flux from
271 the surface, which is then subtracted, see Figure 2.

272 The relative brightness of the remaining oxygen emissions at 1304 Å and 1356
273 Å effectively constrains the primary atmospheric source process (1 and 2). In the
274 GHRS spectra (as well as in all subsequent observations of the near-surface
275 atmosphere), the OI 1356 Å line was consistently brighter by factor of 1.3-2.2.
276 Because the OI 1356 Å transition is spin-forbidden, most processes produce brighter

277 OI 1304 Å emissions. Resonant scattering by oxygen atoms (2) is only effective for
 278 the 1304 Å emission. In the cases of electron-excited emissions, only dissociation of
 279 molecular oxygen, O₂, produces brighter OI 1356 Å emission, while electron impact
 280 on other potential atmospheric species like O, H₂O and CO₂ produces brighter OI
 281 1304 Å emission (Ajello et al. 1971; Makarov et al. 2004; Itikawa 2009). The highest
 282 cross sections for O excitation are measured for electron impact on O and O₂. The
 283 relative excitation rates - calculated with the assumption of Maxwellian distributed
 284 electron population around one core temperature (Figure 3) – unambiguously
 285 differentiates between a primary O atmosphere with an expected 1356-Å/1304-Å ratio
 286 of <0.5, and a primary O₂ atmosphere with an expected ratio of >2. The measured
 287 1356-Å/1304-Å ratio of ~2 and this principal conclusion on the O₂ being the main
 288 source still holds to date. A proposed optically thick pure O atmosphere (Shemansky
 289 et al. 2014) is in fact neither in agreement with any observation of the near-surface
 290 bound atmosphere nor with the theory of optical thickness, and is based on
 291 unsubstantiated assumptions about the plasma conditions for electron excitation, see
 292 Roth et al. (2016) for more details.

293 To derive atmospheric abundances, one needs to consider the properties and flow of
 294 the exciting electrons. The first approach by Hall et al. (1995; 1998) was to make the
 295 simplifying assumption that Europa is surrounded by homogeneous thermal plasma
 296 that constantly excites the atmosphere at a rate given by the temperature and the
 297 density of the electrons and the collisional excitation rates (Figure 3a). They assume
 298 an electron density of 40 cm⁻³ measured by Voyager and a dominant cold component
 299 with $T = 20$ eV, and a $T = 250$ eV hot component with a mixing ratio between hot and
 300 cold of 0.05. For an optically thin atmosphere and constant electron parameters, the
 301 measured brightness I in Rayleighs relates to a column density N along the viewing
 302 direction through

$$303 \quad N [\text{cm}^{-2}] = 10^{10} \frac{I [\text{R}]}{n_e [\text{cm}^{-3}] f(T_e) [\text{cm}^3 \text{s}^{-1}]} \quad (1),$$

304 with the temperature-dependent electron-impact excitation rate $f(T_e)$ and electron
 305 density n_e . Based primarily on the OI1356 Å brightness between 70 R and 90 R and
 306 the uncertainties in the GHRs spectra, Hall et al. (1998) derived a range of (2.4 – 14)
 307 $\times 10^{14}$ cm⁻² for the line-of-sight O₂ column density across Europa's disk.

308 The first disk-resolved observations of the oxygen 1304 Å and 1356 Å
309 emissions were taken in 1999 by HST/STIS. They revealed an irregular pattern with
310 an emission surplus in the northern anti-Jovian quadrant (McGrath et al. 2004; 2009).
311 This inhomogeneity was speculated to be of atmospheric origin (e.g., Cassidy et al.
312 2007), but is likely explained by the inhomogeneous and variable plasma
313 environment, as we will elaborate later.

314 Thereafter, the Ultraviolet Imaging Spectrograph (UVIS) of the Cassini
315 spectrograph measured an extended atomic oxygen atmosphere in addition to the
316 bound molecular oxygen atmosphere (Hansen et al. 2005). The UVIS observations
317 also confirmed the stronger OI 1356 Å emissions in the resolution element covering
318 the moon and the nearest environment and Hansen et al. 2005 also conclude an O₂-
319 dominated bound atmosphere. Additionally, images of visible emissions in eclipse
320 were taken by Cassini's Imaging Science Camera Subsystem (ISS) (Porco et al.
321 2003). The atmospheric brightness of a few kiloRayleigh in the wavelength range
322 between 200 and 1050 nm can possibly originate from various species including
323 oxygen, but were assigned to electron-excited sodium, see next section.

324 During the Jupiter flyby of the New Horizons spacecraft in spring 2007, the
325 ALICE UV imaging spectrograph observed Europa several times. UV spectra were
326 obtained from large distances and the disk of Europa was not resolved. High levels of
327 radiation environment induced noise in the detector combined with high levels of
328 instrument stray light in the instrument in several spectra decreased the data quality.
329 The seven best spectra were combined to improve signal to noise and are presented
330 here in Figure 4. This average UV spectrum, together with the individual spectra of
331 more limited quality, confirmed that the measured disk-averaged 1356-Å/1304-Å
332 ratio of ~2 is consistent and as expected. While STIS was not in operation in 2007,
333 several HST campaigns utilized the Advanced Camera for Surveys (ACS) and the
334 Wide-Field Planetary Camera 2 (WFPC2) to observe Europa's UV and visible
335 emissions. WFPC2 images taken in eclipse with several near-UV and visible filters
336 did not reveal measurable atmospheric emissions, and ACS images in and out of
337 eclipse taken in the same program confirmed the known UV oxygen emissions, but
338 were not analyzed quantitatively (Sparks et al. 2010).

339 A set of four 10-min exposures with the ACS Solar Blind Channel (SBC)
340 F125LP filter was obtained during an eclipse event during the New Horizons Jupiter

341 flyby. These images contain varying levels of foreground Earth airglow background
342 noise. Also the location of Europa within the images is uncertain to within a Europa
343 radius, and a limb brightening morphology in the second image in the series is relied
344 upon for centering the moon disk in their average shown in Figure 5 (middle).

345 Another ACS program provided again hints for an asymmetric oxygen UV
346 morphology, which was compared to tidal stress pattern on surface cracks to assess
347 the possibility of outgassing for the generation of an atmospheric inhomogeneity
348 (Saur et al. 2011). Furthermore, this analysis pointed out a relation of the UV
349 brightness to Europa's position within the magnetosphere.

350 The first spectral UV images taken after the repair of STIS held a surprise. They
351 revealed bright localized hydrogen emission near the south pole in addition to the
352 atmospheric oxygen emissions. The localized nature of these emissions and the
353 relative brightness of the coincident OI 1304 Å emission surplus in the same region
354 are consistent with the existence of local water vapor eruptions on the anti-Jovian
355 southern hemisphere (Roth et al. 2014b). Follow-up observations from early 2014
356 could not confirm an initially hypothesized connection of the detectability of such
357 plume emissions with Europa's orbital position and the changing tidal stresses (Roth
358 et al. 2014a).

359 During a following observing campaign with STIS, aurora UV images were
360 obtained on 15 days between November 2014 until April 2015 at various orbital
361 positions and geometries (Roth et al. 2016). The analysis of the OI 1304 Å and OI
362 1356 Å images from all previous STIS campaigns (1999, 2012, 2014, 2015) provided
363 the most comprehensive picture of Europa's oxygen aurora and its dependencies and
364 systematic changes. The emerging picture is a systematically varying aurora that is
365 closely connected to the changing plasma environment. The emissions are brightest in
366 the polar regions where the ambient Jovian magnetic field line is normal to Europa's
367 disk. Near the equator, where bright spots are found at Io, Europa's aurora is faint
368 suggesting a general difference in how the plasma interaction shapes the aurora at Io
369 and Europa.

370 An unexplained, yet consistently detected characteristic is that the aurora is
371 brighter on the dusk side than on the dawn side. In terms of local time on Europa, the
372 brighter right hemisphere always coincides with the afternoon or dusk region, while
373 the left hemisphere corresponds always with the morning/dawn region. Hence,

374 dependencies of the sources or losses of the atmosphere on the local time through the
375 changing solar illumination could generate such an asymmetry in the atmosphere and
376 aurora. For example, radiolysis rates are temperature dependent hence they possibly
377 differ in the morning and afternoon regions (Plainaki et al. 2013). However, the
378 dusk/dawn asymmetry is not necessarily related to local time effects.

379 The initially detected $1356\text{\AA}/1304\text{\AA}$ brightness ratios from Hall et al. (1995;
380 1998) were generally confirmed by the STIS observations with measured ratios
381 between 1.5 and 2.8 and a mean ratio of exactly 2.0 (Roth et al. 2016). The
382 $1356\text{\AA}/1304\text{\AA}$ ratio decreases with increasing altitude in agreement with a more
383 extended atomic O corona (Hansen et al. 2005), but O₂ prevails at least up to altitudes
384 of 900 km. Differing $1356\text{\AA}/1304\text{\AA}$ line ratios on the plasma upstream and
385 downstream hemispheres require differing O mixing ratio in the near-surface O₂
386 atmosphere as shown in Figure 3(b). While lower ratios on the upstream side are in
387 best agreement with higher O concentration of ~5%, the higher $1356\text{\AA}/1304\text{\AA}$ ratio
388 on the downstream side suggest that hardly any O is present there (1% or less). The
389 difference in abundance is likely related to differences in the production of atomic
390 oxygen. Electron impact dissociation of O₂ is thought to be more efficient on the
391 upstream side, but also longitudinal differences in ion sputtering and radiolysis might
392 have an effect on the O mixing ratio. During several eclipse observations, the aurora
393 does not reveal any signs of systematic changes compared to the sunlit images
394 suggesting no or only weak influence of sunlight on the aurora and an optically thin
395 atmosphere.

396 Shortly before and following the plume aurora detection another effort to
397 probe Europa's neutral gas environment with the Hubble Space Telescope was made
398 by a group around W. Sparks. During several campaigns the moon was observed in
399 and out of transit to search for anomalies around the limb. The results from these
400 observations indeed provided possible supporting evidence for plumes (Sparks et al.
401 2016). The imaging method used in these measurements preclude a spectral
402 identification of the absorbing species as water and/or otherwise.

403 In a recent study, Roth et al. (2017) detected an extended corona of hydrogen, which
404 attenuates Jupiter H Ly-alpha dayglow through resonant scattering. The detected
405 amount of H confirms abundances predicted by Monte Carlo simulations (Smyth &
406 Marconi, 2006).

407 A recent comprehensive assessment of the Galileo plasma measurements near
408 Europa's orbit by Bagenal et al. (2015) shows that the electron density of 40 cm^{-3}
409 commonly assumed to derive atmospheric abundances is in fact at the lower end of
410 the electron densities measured during the Galileo era (1995-2003). So, if the electron
411 density was underestimated, the atmospheric abundances were potentially
412 overestimated when using the simple conversion after Equation (1). Figure 3(c) shows
413 brightness isolines as a function of both neutral column density and electron density
414 for the approximate range reported by Bagenal et al. (2015). It is important to keep in
415 mind here that the aurora brightness is always a measurement of the product of the
416 two densities. Derived atmosphere abundances are therefore subject to the uncertainty
417 of the plasma environment in addition to the fact that the non-linear processes of the
418 aurora generation and the electro-dynamic interaction of the atmosphere with the
419 magnetosphere (e.g., Kivelson et al. 2004; Saur et al. 1998) are neglected in Equation
420 (1).

421 ***2.1.2 Visible observations of trace species***

422 The sodium atmospheric component was discovered in 1996 by Brown and Hill
423 (1996), who detected the emission lines at $5890\text{--}5896 \text{ \AA}$ of an extended escaping
424 component up to $25 R_E$. The Na D_2/D_1 ratio of 1.7 was consistent with resonantly
425 scattered sunlight by an optically thin atmosphere from which a surface density of
426 $\sim 70 \text{ atoms cm}^{-3}$ was derived. Its origin is still debated, whether it is endogenic, i.e.,
427 coming from Europa's subsurface and released from the surface via radiolysis of
428 hydrated salts, or exogenic and coming from Io extended sodium cloud. A column
429 density of $\sim 10^{10} \text{ cm}^{-2}$ was derived (Brown 2001).

430 Potassium in the extended exosphere of Europa was first observed in 1998
431 (Brown 2001) using Keck/HIRES. Simultaneous observations of potassium and
432 sodium were performed and the Na/K ratio of 25 ± 3 was derived. Vertical profiles in
433 the region between 5 and 15 Europa radii (R_E) were obtained and column densities of
434 $(5\text{--}15) \times 10^7 \text{ cm}^{-2}$ for K, and $(1\text{--}4) \times 10^9 \text{ cm}^{-2}$ for Na derived. The Na/K ratio results to
435 be intermediate between values measured elsewhere in the solar system, ranging from
436 2 in the Earth crust up to almost 200 on Mercury's surface (Potter and Morgan, 1997;
437 Killen et al. 2007), with the solar system value being 15 (Loggers and Fegley 1998),
438 and very close to cosmic abundance value of 20 (Allen 1991). The icy surface of
439 Europa and resurfacing processes with salt deposition and aqueous alteration are

440 surely involved in the Na/K ratio, probably leading to different ratios in the gaseous
441 (exosphere), solid (surface) and liquid (subsurface) components. A recent report by
442 Hörst and Brown (2013) of a search for atmospheric magnesium at the strong 2852 Å
443 resonant scattering emission line using HST/FOS data only provided upper limits. The
444 derived Mg column density upper limits of $2 \cdot 10^{10} \text{ cm}^{-2}$ at $8.8 R_E$ and $9 \cdot 10^9 \text{ cm}^{-2}$ at 14.4
445 R_E indicate that the Mg abundance in Europa's atmosphere is lower than meteoritic
446 and cosmic abundances, giving rise to two possible explanations: either Mg is not
447 present in the surface at sufficient abundance, the release process of sputtering is less
448 efficient compared to Na and K, or the Na and K on Europa's surface are enhanced by
449 a contribution from Io.

450 Modeling of the sodium exosphere (Leblanc et al. 2002) used a 3D Monte
451 Carlo model to reconstruct source processes, energy distribution, and flux of ejected
452 Na. The dominant release process is confirmed to be ion-induced sputtering that,
453 acting on a water ice surface, will produce the inferred and observed column densities
454 of O_2 , Na and K. Na is released in the atomic form plus a small component as NaO or
455 NaS; its ejection velocity and spatial distribution depends on the surface regions in
456 terms of the proportion of ices or refractory species. Estimated exospheric loss of Na
457 is $(5-10) \times 10^6 \text{ atoms cm}^{-2} \text{ s}^{-1}$. The model reproduces Na cloud asymmetries in both the
458 –orbital plane due to the combined effects of Jupiter and Io, and in the vertical plane
459 due to the combined effect of the centrifugal force and the gravity of Jupiter.
460 Comparison with observed emission profiles at $20 R_E$ and beyond by Brown (at Keck
461 in 1999 as reported in Leblanc et al. (2002)) help constrain the low energy
462 component, the energetic tail component, and the background component
463 respectively. In particular, an energetic tail occurs when corotating ions (O^+ and S^+ of
464 tens of keV to MeV) and electrons sputter into a material with high excitation density
465 (Johnson 1990). The background component instead can be produced by three
466 possible sources: NaX dissociation, sputtering of dust grains and iogenic Na cloud.
467 The latter is supported by the observed temporal variations. Finally, the sputtered Na
468 flux is calculated to be $3 \cdot 10^7 \text{ cm}^{-2} \text{ s}^{-1}$, of which 60% returns to the surface (+10% of
469 NaX) and 40% escapes. The net loss rate is $(5-10) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ and implantation rate
470 for iogenic Na is $(0.2-0.8) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$; hence, the observed Na is likely of endogenic
471 origin or another source is required to explain such values. The model is improved in
472 Leblanc et al. (2005) by including leading/trailing asymmetry of ejecta,

473 photoionization and heavy ions sputtering by O^{n+} and S^{n+} as source processes,
474 interaction with the O_2 atmosphere and it is compared to an additional set of data.

475 Cipriani et al. (2008; 2009) update the model to account for non-uniform Na
476 density distribution on the icy surface and for ejection of Na atoms by solar UV
477 photons, and then apply it also to potassium, using the Na/K ratio as measured by
478 Brown (2001). Three regions are identified with different values: beyond $3 R_E$ where
479 $Na/K = 20-25$, between 1.5 and 2 where $Na/K = 7$, and between the two where a steep
480 increase occurs. Depletion of K with increasing altitude is the reason for such profile,
481 for the minimal energy required by Na atoms to reach $3 R_E$ is half the value needed by
482 K. If Na average source rate is $3 \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, then average K source rate is $1.8 \cdot 10^5 \text{ cm}^{-2}$
483 s^{-1} . Ionization altitude for Na is 230 km and for K is 200 km; that is 16% Na and
484 4.5% K are ionized.

485 **2.2. Summary of the plasma and magnetic field observations and of their** 486 **implications in Europa's exosphere**

487 To investigate the plasma environment of Europa, it is necessary to consider the Io
488 plasma torus and its effect on the environment of Europa. Pioneer 10 in 1973
489 provided in-situ plasma measurements, which were interpreted in terms of iogenic
490 plasma only after the Voyager flybys (Intriligator and Miller 1981). Voyager 1 (1979)
491 made a closest approach to Jupiter well inside Io's orbit and measured ion and
492 electron properties of the Io plasma torus (Bagenal et al. 1980; Sittler and Strobel
493 1987). The Unified radio and Plasma Wave Experiment onboard Ulysses spacecraft in
494 1992 measured electron properties from plasma waves detected as Ulysses made a
495 vertical cut through the Io torus at $\sim 8 R_J$ (Hoang et al. 1993) and indicated that the
496 torus electrons have supra-thermal tails. The plasma environment between Io and
497 Europa is shown in Figure 7.

498 In 1995 with the arrival of Galileo spacecraft into orbit around Jupiter, the
499 region around Io and Europa was visited several times. Observations from the Galileo
500 plasma analyser (PLS) during two near encounters with Europa (E4 and E6 orbits)
501 showed that the ions near Europa are a mix of thermalized torus plasma with
502 approximately Maxwellian ion velocity distributions and partially thermalized pickup
503 ions with ring distributions (Paterson et al. 1999). Based on these measurements,
504 plasma moments, ion number densities, bulk flow velocities and ion temperatures
505 were determined.

506 Bagenal et al. (2015) re-analyzed the PLS data to derive density, azimuthal
507 speed and temperature, assuming that the dominant heavy ion species have an
508 effective mass to charge ratio (M/Q) of 12 (Delamere et al. 2005) and using a
509 forward-modeling technique to model a single isotropic Maxwellian ion species.
510 Figure 8(a) shows the ion temperature as function of electron density derived from
511 Galileo measurements between 8.9 and 9.9 R_J . Measurements within $\sim 2.5 R_E$ of
512 Europa are excluded, because they could have been affected by the plasma-moon
513 interactions. The temperatures seen in Figure 8(a) are similar to those reported by
514 Paterson et al. (1999). The electron density and ion temperature are inversely
515 correlated, which is indicative of radiative cooling of the torus increasing at higher
516 densities. Before flyby E12, the Plasma Wave Instrument (PWS) (Kurth et al. 2001)
517 measured a particularly high density, while during E12 the magnetic fields were
518 anomalously strong (Kivelson et al. 2009). These transient variations could be related
519 to activity at Europa or to the fact that iogenic plasma passed by Galileo as it
520 approached Europa.

521 The local electron density, N_e (measured by PWS), and the ion temperature
522 and azimuthal speed (measured by PLS) are shown in the histograms of Figure 8(b).
523 The azimuthal velocity presents a narrow distribution, while the density and
524 temperature distributions have low- and high-energy tails, respectively.

525 The magnetic field around Europa has been investigated based on Galileo
526 magnetometer measurements. Schilling et al. (2004) investigated the presence of a
527 fixed dipole moment in the interior of the moon, based on data acquired during four
528 passes by Europa. They suggested a small contribution of a permanent dipole moment
529 with an upper limit of 25 nT, which is small compared to the magnitude of the
530 induced magnetic field. Figure (9) shows the observed and modeled field for a Europa
531 flyby, as reported by Schilling et al. (2004)..

532 Europa's orbital eccentricity (0.0094) produces a ~ 30 nT variation in the
533 magnetic field magnitude. Figure (10) provides a statistical view of the magnetic field
534 experienced by Europa (Bagenal et al. 2015). The histograms are constructed based
535 on binning of the values of the three model field components B_r , B_{th} , B_{ph} and the
536 magnitude B_{mag} of the internal VIP4 (Connerney et al. 1998) and the Khurana model
537 (Khurana 1997) at Europa's mean orbital distance. Even though the neutral gas
538 environment of Europa is tenuous is still a barrier to magnetospheric ion

539 bombardment. The magnetospheric plasma flow diverts around Europa due to the
540 ionospheric conductivity (Saur et al. 1998).

541 **2.3. ENA observations of Europa's neutral torus**

542 Charge-exchange Energetic Neutral Atoms (ENAs) have been observed in Jupiter's
543 magnetosphere already by Voyager in 1979 (Kirsch et al. 1981a,b; Cheng 1986) and,
544 with more accuracy, by Cassini during the Jupiter flyby in late 2000/early 2001, when
545 the Ion and Neutral Camera INCA, one of three sensors of the Cassini
546 Magnetospheric Imaging Instrument MIMI (Krimigis et al. 2004), obtained the first
547 images of Jupiter's magnetosphere in Energetic Neutral Atoms (ENA) flux (Krimigis
548 et al. 2002).

549 These ENAs originate from the charge-exchange interactions between the
550 energetic ions in the plasma of the Jovian magnetosphere with the planet's exosphere
551 and the volcanic gases from Io and Europa (Krimigis et al. 2002). The resulting
552 neutrals maintain the species, the energy and the direction of the parent ions and,
553 being not affected anymore by the electromagnetic forces, travel in ballistic orbits
554 reaching large distances from their generation region. The detection of these energetic
555 atoms permits to have a global view of the plasma environment.

556 INCA is a time-of-flight instrument that separately analyzes the composition
557 and velocity of ENAs. It has a $120^\circ \times 90^\circ$ field of view with an angular resolution of
558 approximately $7^\circ \times 7^\circ$, depending on particle energy (Krimigis et al. 2004).

559 Measurements show that a continuous flow of fast energetic neutral atoms in the
560 velocity range 10^3 to 10^4 km s⁻¹ are emitted within $30 R_J$ of Jupiter (Figure 11). ENAs
561 are emitted from both polar and equatorial regions of the Jupiter's magnetosphere
562 appearing to be most intense in the vicinity of Io's and Europa's plasma torus.

563 The closest Cassini distance to Jupiter was around $140 R_J$. Given the
564 instrument angular resolution, it was not possible at this distance to ascertain the
565 detailed Jupiter ENA source regions using the raw ENA images. Mauk et al. (2003)
566 removed some instrumental distortions by using a point spread function (PSF) derived
567 using images of Jupiter taken from distances beyond than $800 R_J$. Processed 50-80-
568 keV ENA images (15 h of integration time) of Jupiter's magnetosphere from $140 R_J$,
569 show that a central feature centered on Jupiter, and two outermost features just
570 beyond the orbit of Europa at $9.5 R_J$ (Mauk et al. 2003) (Figure 12). The brightest
571 emissions come from lines of sight that pass through the largest volume of the

572 emission region. From this image the estimated total emission rate of the torus trans-
573 Europa, 50-80 keV, is $0.8 \cdot 10^{24} \text{ s}^{-1}$ (Mauk et al. 2003). By assuming H^+ on H (or H_2)
574 charge-exchange interactions, given the ion measurements by Galileo (Williams et al.
575 1996) and the known cross sections, the total number of atoms or molecules in the
576 volume is $N = 4.5 \cdot 10^{33} \pm 20\%$, double of this value if radial symmetry about Europa's
577 orbit (and not only contributions outside of Europa's orbit) is considered. If a volume
578 with a radial extent and a height of $2 R_J$ is considered, the estimation of neutral gas
579 density is about 40 atoms cm^{-3} (Mauk et al. 2003). This density is by a factor of 50
580 (Cheng, 1986) to 100 (Mitchell et al. 1996) larger than that expected on the basis of
581 dispersal of neutral gases from Io, but seems in agreement with the estimation derived
582 by Lagg et al. (2003) on the basis of angular distributions of the hot ions at the Europa
583 orbit, affected by the loss due to charge exchange with Europa's neutral torus. By
584 considering the whole energy range of ENAs Mauk et al. (2003) estimated an ENA
585 emission rate of 10^{25} s^{-1} , which even if it is a smaller rate than the one estimated for
586 Io, 10^{28} s^{-1} , it emits a similar energy (Smyth and Marconi, 2000), about 10^{12} W .

587 The exosphere loss rates from Europa, ranging from $5 \cdot 10^{26} \text{ s}^{-1}$ (Cooper et al.
588 2001) to $4 \cdot 10^{27} \text{ s}^{-1}$ (Saur et al. 1998) are 1–2 orders of magnitude less than the S and O
589 source from Io (Smyth and Marconi 2000). So, either the Io torus loss rates are indeed
590 1–2 orders of magnitude larger than the loss rates from Europa or the source rates for
591 gases at Europa have been underestimated. On the other hand, charge exchange is not
592 the major loss responsible for ions in the inner Jovian magnetosphere (Europa to Io).
593 During the Voyager epoch, Thorne (1982) argued that ions scattering with EMIC
594 waves in the plasma have much higher potential for generating ion loss than charge
595 exchange. He argued additionally that radial and pitch angle distributions measured
596 by Lanzerotti et al. (1981) favor the predominance of EMIC interactions over charge
597 exchange losses.

598 These ENA measured by INCA are dominated by hydrogen atoms in the
599 energy range from a few to 100 keV, emitted from the planet's exosphere and neutral
600 gas tori near the inner Galilean satellites (Mitchell et al. 2004). Heavier ions (likely a
601 mixture of oxygen and sulphur) comprise a significant fraction of the ENA flux in the
602 0.1–1.0 MeV total energy range. During a period of about 80 days, FR^2 (flux*
603 of the distance) is constant to lowest order (Figure 13(a)), showing that the ENA are
604 radiating from the inner region without any further source or sink (Mitchell et al.

605 2004). The INCA observed variations were close to the statistical limit of its
606 measurement, thus the Jupiter's magnetosphere was fairly stable in that period.
607 Mitchell et al. (2004) estimated a source rate of $\sim 10^{26}/s$ H in the 10–100 keV range
608 and $5 \cdot 10^{25}/s$ O in the 100–1000 keV energy range.

609 The derived energy spectra obtained by CASSINI/INCA and by
610 Voyager/LECP are shown in and compared in Figure 13(b). The derived ENA
611 spectrum based on the LECP-data is an upper limit at $100 R_J$ since the instrument was
612 not able to distinguish between X rays or ENAs (Kirsch et al. 1981). Since ENA
613 species could not be determined from the Voyager data, these upper limits are plotted
614 in figure assuming either pure hydrogen or pure oxygen (see also Cheng, 1986).

615 In summary, Mauk et al. (2003) located the ENA source peaked at the Europa
616 neutral gas torus, concluding that the Europa source is more powerful than the one at
617 Io. This produces a significant fall-off of energetic ion population moving radially
618 inward from Europa's orbit to Io's one, due to the efficient Charge-exchange
619 collisions with ambient neutrals (Paranicas et al. 2003). Data from Cassini
620 MIMI/INCA suggest that the ENA flux propagate outward without relevant
621 modification (Mitchell et al. 2004).

622 The ENA images obtained during the Jupiter flyby have been further analyzed
623 for any potential asymmetries by studying images accumulated for 4-5 h during which
624 pointing was stable and therefore consists of a subset of the images analyzed by Mauk
625 et al. (2004). Hydrogen images in the 55-90 keV energy range were analyzed rather
626 than the lower energy channels where the point-spread function of the INCA imager
627 becomes wider. The neutral gas distribution was retrieved by employing a forward-
628 modeling technique using a parametric function to describe the neutral gas and
629 assuming the radial distribution of energetic protons obtained by Galileo/EPD (Mauk
630 et al. 2004). Here, the neutral gas has been assumed to consist of H_2 to be consistent
631 with the calculations of Smyth and Marconi (2006). Note that the ENA image alone
632 cannot be used to differentiate the neutral gas composition. Figure 14 (upper panel, a)
633 displays the observed INCA hydrogen image accumulated over 13:06-17:31 UTC on
634 2 January 2001. An enhancement over Europa's position can be seen that is about a
635 factor of three higher than that on the opposite side of Jupiter. It has to be emphasized
636 again that the INCA point-spread function at this distance results in a significant blur

637 in the image and that without the instrumental PSF the emission region is significantly
638 smaller.

639 Figure 14 (upper panel, b) shows the resulting best-fit simulated image
640 constructed by keeping the model energetic proton distribution fixed while adjusting
641 the parametric neutral gas model until the reduced chi-square difference between the
642 observed and simulated images is minimized. The simulation takes in to account the
643 instrumental PSF, the Compton-Getting effect (Gleeson and Axford, 1968) and
644 applies counting noise assuming a Poisson distribution. The resulting neutral gas
645 distribution required for the best fit between the observed and simulated ENA images
646 is presented in Figure 14 (lower panel, left). During the accumulation time, Europa
647 moved a relatively small distance as indicated by the arrow. The first conclusion to be
648 made is that the ENA images in this time range are consistent with an asymmetric
649 Europa gas torus, and consequently the term “torus” is misguided. Note that the center
650 of the neutral gas distribution is approximately 30° ahead Europa in its orbit, which
651 there is no explanation for at this stage. Because the energetic proton distribution is
652 assumed to be relatively confined to the magnetodisc and because the proton
653 intensities fall off rapidly inside of Europa’s distance and decrease more gradually
654 beyond Europa’s distance, retrievals of the neutral gas using ENA images are most
655 sensitive to the azimuthal asymmetry of the neutral gas distribution around Europa’s
656 orbital distance and less sensitive to the exact radial and vertical distributions. To
657 illustrate the effects of the PSF, Figure 14 (lower panel, right) shows the simulated
658 image without the PSF applied or noise applied. As expected, the emission region is a
659 relatively thin region and the azimuthal asymmetry is about one order of magnitude
660 between the line-of-sight (LOS) intersecting Europa’s orbit on the right ansa
661 compared to the left ansa.

662 From these simulations one can also derive the expected temporal variation in
663 the ENA intensities that would come from the magnetodisc wobbling up and down
664 over the Europa gas torus. In the INCA images, this effect would produce a factor of
665 2-3 variation in the observed intensities, consistent with the observations (Mitchell et
666 al. 2004). However, stronger variations could of course be present due to a temporal
667 variability in the energetic proton intensities because of the large-scale injections
668 thought to occur in the Jovian magnetosphere (Krupp et al. 1998), also pronounced in

669 the Saturnian (Mitchell et al. 2009) and Terrestrial magnetospheres (Brandt et al.
670 2002).

671 **3. Europa's environment: current state of modeling**

672 **3.1 Comparison of Europa plasma and MHD models and possible future** 673 **improvements**

674 Since the close encounters of the Galileo spacecraft with Europa, a number of
675 numerical models have been developed to understand the plasma interaction with
676 Europa and its atmosphere, and to provide global context for interpreting Galileo
677 observations. These models were based on different assumptions and adopted
678 different approaches. Here we provide an overview of the various plasma models of
679 Europa's plasma interaction focusing on published magnetohydrodynamic (MHD)
680 models and physics-chemistry models.

681 ***3.1.1. Plasma and MHD model description and main results***

682 ***Two-fluid plasma model by Saur et al. (1998)***

683 The main purpose of the model developed by Saur et al. (1998) is to study the
684 interaction of Jupiter's magnetosphere with Europa's atmosphere/ionosphere taking
685 into account a self-consistent treatment of the coupling of the plasma interaction and
686 the atmosphere. The authors also aim to investigate the plasma driven sources and
687 sinks that maintain the neutral atmosphere. The Saur et al. (1998) model is a steady-
688 state, 3D two-fluid (electron and a single ion species O^+) plasma model and is based
689 on the various current systems driven in the interaction. Charge exchange, collisions
690 between the ions and the atmospheric neutrals and electron impact ionization processes
691 are included in the model. The authors estimate that the electron impact ionization is
692 the dominant ionization process in Europa's environment and that photoionization is
693 over an order of magnitude smaller. The model computes self-consistently plasma
694 density, plasma velocity, electron temperature of the thermal and the suprathermal
695 electron population, electric current and electric field in the vicinity of Europa but
696 assumes a spatially constant background magnetic field. The model accounts different
697 source and loss processes of the atmosphere: The pickup loss, atmospheric sputtering,
698 and surface sputtering by torus ions and secondary ions.

699 Europa's atmosphere is assumed to consist of O₂ molecules. Saur et al. (1998)
700 assume that the atmospheric surface density decreases from the trailing to the leading
701 hemisphere according to the calculations of the normalized flux of ions to the surface
702 of Europa by Pospieszalska & Johnson (1989). Assuming an average scale height of
703 145 km based on constraints from the HST observations by Hall et al. 1995, they infer
704 a vertical O₂ column density of $5 \times 10^{18} \text{ m}^{-2}$ by considering the atmospheric mass
705 balance between surface sputtering and atmospheric loss. The true spatial structure of
706 Europa's atmosphere is likely more complex and affected by various cooling and
707 heating mechanisms, loss and source mechanisms among others. Additionally, Saur et
708 al. (1998) apply one independent observational constraint that the atmosphere emits
709 the radiation observed by HST (Hall et al. 1995). For these model parameters the
710 location of the exobase is at 71 km.

711 Saur et al. (1998) show that Europa's atmosphere and the plasma interaction
712 are strongly coupled and influence each other. The neutral atmosphere is generated,
713 removed, and maintained by sputtering processes, which strongly depend on the
714 electrodynamic conditions at Europa. The Pedersen and Hall conductivities in
715 Europa's ionosphere control the diversion of the plasma flow and allow only about
716 20% of the upstream plasma to reach the surface of Europa according to the model
717 (shown in Figure 15). At the flanks of the moon the plasma flow is accelerated. The
718 influence of the Hall effect is small and therefore the symmetry of the plasma flow in
719 the ionosphere is only slightly disturbed compared to the unperturbed flow. The
720 distribution of the electron density shows a local maximum with a value of
721 1000 cm^{-3} at the upstream surface and a global maximum of nearly 9000 cm^{-3} ,
722 which is in general agreement with densities derived from radio science
723 measurements by Kliore et al. (1997). Regions with high electron density can be
724 mapped to regions with low electron temperature with a global minimum of 8 eV. A
725 total current of $7 \times 10^5 \text{ A}$ is driven in each Alfvén wing.

726 A balanced neutral atmosphere mass budget for production and loss of O₂ is
727 found for a total O₂ release from the surface of $8.5 \cdot 10^{26} \text{ s}^{-1}$ corresponding to a net
728 atmospheric loss of 50 kg s^{-1} . The model shows that the atmospheric loss through
729 sputtering dominates pickup loss by about a factor of 10. Primary sputtering by
730 energetic magnetospheric ions strongly exceeds resputtering. Thus sputtering by
731 ionospheric ions is not a major source of Europa's atmosphere. The reason is that the
732 electric field close to the moon is strongly reduced by the electrodynamic interaction.

733 Consequently, ionospheric ions do not get enough energy from pickup processes to
734 sputter efficiently Europa's surface.

735 ***Single-fluid MHD model by Schilling et al. (2007, 2008)***

736 The main purpose of the model developed by Schilling et al. (2007; 2008) is to study
737 self-consistently the effect of the internally induced magnetic field from a subsurface
738 conductive layer on the interaction of Europa's atmosphere with Jupiter's
739 magnetospheric plasma. It is the first model that considers the contribution to
740 induction in Europa's ocean generated by the time-dependent plasma magnetic field.
741 The aim is to constrain the conductivity and thickness of the conductive layer. The
742 Schilling et al. model is a 3D single-fluid MHD model which includes the plasma
743 currents in the atmosphere and the plasma in the vicinity of Europa. Additionally, the
744 model accounts self-consistently for induction in a three-layered conductive shell
745 model in the interior of the moon. The interaction above Europa's surface is described
746 by modified MHD equations that consist of one evolution equation for the plasma
747 density ρ , the plasma bulk velocity \mathbf{u} , the magnetic field \mathbf{B} and the internal energy E .
748 Time-varying background magnetic field of Jupiter and the magnetospheric current
749 sheet B_0 , magnetic field caused by the interaction of the magnetospheric plasma with
750 Europa's atmosphere B_p , induced magnetic fields from the interior due to the time-
751 varying background field $B_{ind}(B_0)$ and induced fields due to the time-varying plasma
752 magnetic fields $B_{ind}(j_p)$ are included in the model.

753 The Schilling et al. model takes into account plasma production P and loss L
754 due to electron impact ionization and dissociative recombination. Moreover, it
755 includes momentum transfer due to collisions between the ions/electrons and the
756 neutrals via collision frequencies ν_{in} and ν_{en} , respectively. The major source for the
757 generation of ionospheric ions is electron impact ionization. Newly created
758 ionospheric electrons are much cooler than the magnetospheric electrons and are not
759 involved into the ionization process. Thus the authors consider the magnetospheric
760 and the newly produced ionospheric electrons separately by assuming a separate
761 continuity equation for the magnetospheric electrons. Thereby they ensure that impact
762 ionization does not change the number of the magnetospheric electrons. The
763 production of ionospheric electrons by electron-impact ionization is strongly
764 temperature dependent. In the model the magnetospheric electron temperature is not
765 calculated self-consistently. To avoid an overestimation of the production rate and to

766 account for the conservation of energy they follow Saur et al. (1998) and describe
767 analytically the spatially dependent electron temperature, so that the electron
768 temperature is decreased strongest close to the surface and on the flanks. They
769 determine the analytical description of the temperature by comparing the model with
770 measurements of Galileo flybys.

771 Schilling et al. (2007; 2008) use a hydrostatic molecular oxygen atmosphere
772 with a scale height of 145 km and a surface density of $1.7 \cdot 10^7 \text{ cm}^{-3}$ similar to Saur et
773 al. (1998). They adopt the description of the variation of the neutral number surface
774 density in Europa's atmosphere from Saur et al. (1998), with maximum O_2 neutral
775 densities on the trailing side of the moon and lower densities on the leading
776 hemisphere. The simulations were performed with the 3D time-dependent ideal MHD
777 code ZEUS3D.

778 A consistent description of Europa's interior is given by the concept of virtual
779 plasma. Europa's interior is described by a plasma, which mimics the non-conducting
780 properties of an icy crust. For the description of the upstream magnetospheric plasma
781 Schilling et al. (2007; 2008) apply an average ion mass of 18.5 amu and an effective
782 ion charge of 1.5 (Kivelson et al. 2004). The magnetospheric electrons at Europa
783 consist of a thermal population with a temperature of 20 eV and a supra thermal
784 population with a number density of 2 cm^{-3} at a temperature of 250 eV (Sittler & Strobel
785 1987). The thermal plasma density varies with the position of Europa in the plasma sheet
786 with a minimum electron number density of 18 cm^{-3} when Europa is outside the plasma
787 sheet and a maximum value of 250 cm^{-3} when Europa is in the center of the plasma
788 sheet. Therefore, they assume the plasma density to fall off with $\exp(-(|z_{\text{CS}}|/H)^2)$
789 perpendicular to the plasma sheet plane, where $H = 0.7 R_J$ is the scale height of the
790 plasma sheet with Jupiter's radius R_J and z_{CS} is the distance of Europa from the center
791 of the plasma sheet (Thomas et al. 2004; Schilling et al. 2007).

792 Schilling et al. (2007) show that the spherical harmonics coefficients of the
793 plasma induced magnetic fields are an order of magnitude smaller than the spherical
794 harmonics coefficients of the background magnetic field induced dipole. They
795 conclude that the influence of the fields induced by the time variable plasma
796 interaction is small compared to the induction caused by the time-varying
797 background field. Moreover, they compare their model results with the Galileo
798 Magnetometer data along the trajectories of the flybys E4, E14 and E26. Thereby

799 they concentrate on flybys that occurred when Europa was located outside the
800 current sheet so that the influence of induced fields is strongest. From the
801 comparison with the observed data as shown in Figure 16 they derive constraints
802 on the conductivity and the thickness of Europa's subsurface ocean. They find for
803 the conductivity of the ocean values of 500 mS/m or larger combined with ocean
804 thicknesses of 100 km and smaller to be most suitable to explain the magnetic
805 flyby data (Schilling et al. 2007).

806 Schilling et al. (2008) have shown that the Alfvén current system is
807 deformed and displaced due to the influence of the induced fields in the
808 subsurface ocean as shown in Figure 17. These findings are in agreement with
809 theoretical considerations (Neubauer 1999) and observations (Volwerk et al. 2007).
810 They determine a similar total Alfvén wing current through the northern Alfvén
811 wing of $7 \cdot 10^5$ A as Saur et al. (1998). Another effect of the induction is that the
812 plasma wake of Europa is deformed and the enhanced density downstream of
813 Europa is concentrated in a smaller region of the wake. With their model results
814 they are able to explain the high ionospheric densities measured by Kliore et al.
815 (1997) and the ion number densities measured by Paterson et al. (1999) in the wake
816 along the E4 trajectory (Schilling et al. 2008).

817 The asymmetries in the current and plasma density are time varying. Their
818 results demonstrate that the effect of induced magnetic fields is observable in the
819 Alfvén wings and the plasma wake at large distances from Europa where the induced
820 fields are negligible. Therefore a fully self-consistent implementation of the induction
821 into the MHD equations was necessary.

822 ***Single-fluid MHD model by Kabin et al. (1999)***

823 Kabin et al. (1999) developed the first MHD model of Europa's plasma interaction
824 based on the code BATSRUS (Block-Adaptive Tree Solar wind Roe-type Upwind
825 Scheme), which has been described in detail by Powell et al. (1999). The Kabin et al.
826 model was a 3D single-fluid MHD model that solved the ideal MHD equations with a
827 finite-volume, high-order numerical scheme on an adaptively refined unstructured
828 grid that allows resolving the near-Europa region with fine grid resolution while
829 having a simulation domain large enough to include the upstream and wake regions.
830 The model incorporated source and loss terms in the MHD equations to describe
831 various mass-loading processes occurring in Europa's environment, including

832 ionization, charge-exchange, and recombination with specified constant reactions
833 rates. Furthermore ion-neutral interaction was modeled by a friction force that served
834 as a sink for momentum of the plasma. In applying this model to Europa, the authors
835 also explored different boundary conditions for the inner boundary that represents
836 Europa's surface to examine the sensitivity of model results on boundary conditions
837 and to understand the detailed interaction of the surface with the plasma and the
838 fields.

839 The MHD model was run for the Galileo E4 flyby conditions with the
840 upstream environment conditions based on measured magnetic field and plasma data.
841 The model results from runs with different inner boundary conditions were then
842 compared with Galileo plasma and fields measurements (Kivelson et al. 1997; Gurnett
843 et al. 1998; Paranicas et al. 1998) along the E4 flyby trajectory. The authors found
844 that a model that included an induced internal dipole and an upstream flow rotated by
845 $\sim 20^\circ$ from the corotation direction appeared to best match the observations. The
846 induced dipole included in the model that reproduced observations had roughly the
847 same orientation as that inferred from magnetometer analysis by Khurana et al. (1998)
848 but with a smaller magnitude. The total mass-loading rate required for the best fit
849 amounted to 3.75 kg/s.

850

851 *Two-species MHD model by Liu et al. (2000)*

852 Liu et al. (2000) extended the Kabin et al. MHD model by developing a two-species
853 MHD model that included the ambient Jovian plasma (assumed to consist primarily of
854 atomic oxygen ion, O^+) and the molecular oxygen ions (O_2^+) originating from
855 Europa's ionosphere as two separate ion species. Specifically, the two ion species
856 were modeled by separate continuity equations but shared the same momentum and
857 energy equations in the MHD simulation. This treatment allowed to obtain separate
858 distribution of plasmas originating from Jupiter's magnetosphere and Europa's
859 ionosphere, which were merged into one plasma fluid in the previous single-species
860 MHD model by Kabin et al. Other aspects of the Liu et al. model were essentially the
861 same as the Kabin et al. model, such as the inclusion of an induced dipole and the
862 prescription of mass-loading terms in the MHD equations.

863 The model was also run for the Galileo E4 flyby conditions and compared
864 with Galileo observations. While the general agreement between the model and data

865 is similarly good compared to the previous MHD model, the two-species model did
866 provide additional insights into the plasma interaction at Europa. For instance, it
867 became clear from the comparison with the Galileo PWS observations of electron
868 density (Gurnett et al. 1998) along the E4 flyby that the double peaks in electron
869 density observed near closest approach and the central wake were both caused mainly
870 by O_2^+ originating from Europa. The two-species model also allowed the authors to
871 obtain an estimate of the escape flux of Europa's ionospheric plasma down the tail,
872 which was found to be about $5.6 \cdot 10^{25}$ ions/s or 3 kg/s.

873

874 ***Multi-fluid MHD model by Rubin et al. (2015)***

875 Taking advantage of increased computational resources available and a suite of
876 improvements of the BATSRUS model (Toth et al. 2012) made in recent years, Rubin
877 et al. (2015) developed a multi-fluid MHD model for Europa's plasma environment.
878 Different from the previous two-species MHD model by Liu et al. (2000), the multi-
879 fluid model treats multiple ion species as separate fluids with their own continuity,
880 momentum and energy equations. In addition, the electrons are modeled as a separate
881 fluid. The electron pressure evolution was solved to calculate the electron temperature
882 in a self-consistent manner. The electron heat conduction along magnetic field lines
883 was also considered. These electrons provide an important source of ionization that
884 helps maintaining Europa's ionosphere, as previously suggested by Saur et al. (1998).

885 In a brief summary, this model included a wide variety of processes, such as
886 ionization due to both photo-ionization and electron impact ionization, charge-
887 exchange, ion-electron recombination, elastic collisions and electron cooling and
888 heating. The model adopted an analytical description for Europa's exosphere, which
889 is a combination of two exponential functions representing the thermal and sputtered
890 components of the exosphere (e.g., Cassidy et al. 2007). Such a setup required a
891 highly resolved grid on the order of 10 km near the surface of Europa. Moreover, in
892 the neutral model the neutral density on the trailing hemisphere was assumed to be
893 higher than that on the leading hemisphere due to increased sputtering. The average
894 column density corresponding to the neutral model used was $\sim 1.6 \cdot 10^{16} \text{ m}^{-2}$, which is
895 consistent with the column density $(1.5 \pm 0.5) \cdot 10^{19} \text{ m}^{-2}$ derived from HST observations
896 (Hall et al. 1995). Many of the reaction rates associated with various plasma-neutral
897 interactions were then calculated based on parameters directly derived in the

898 simulation, such as the densities and temperatures of individual species. For instance,
899 the modeled electron temperature was used to calculate the impact ionization rate, the
900 recombination rate, as well as the elastic collision rates of electrons with ions and
901 neutrals. The energy required to ionize a neutral particle has to be provided by the
902 impacting electron, which in turn lowers the electron temperature. Therefore the total
903 mass loading of plasma around Europa is not a pre-defined input but a result of the
904 model calculation.

905 As an initial application of the multi-fluid model, Rubin et al. (2015)
906 simulated the Galileo E4 and E26 flybys with a three-fluid model. In this simulation,
907 the first fluid consists of oxygen ions (O^+), mostly from Jupiter's magnetosphere with
908 a minor contribution from dissociated and ionized O_2 from Europa's oxygen
909 exosphere. The second fluid represents the molecular oxygen ions (O_2^+) originating
910 from mass-loading through impact ionization, photoionization, and charge-exchange
911 of the plasma ions with the neutral exosphere. The third fluid corresponds to the
912 electrons, which were treated as a charge-neutralizing fluid (MHD). As an example,
913 Figure 18 shows plasma density distribution near Europa for both O^+ and O_2^+ . One
914 prominent feature that stands out from the figure is that the multi-fluid MHD model
915 produces some asymmetries in the plasma density distribution. Such asymmetries are
916 consistent with that expected from the physics of the interaction of different plasma
917 populations, i.e., due to the velocity difference between the electron and the ion
918 fluids: on the trailing hemisphere (upstream side) the plasma density of the
919 magnetospheric population is enhanced on the Jupiter facing side (positive E_{phiO} -y
920 side) whereas the density of the pick-up ions is enhanced on the anti-Jovian side.

921 The model results were in good agreement with the Galileo magnetometer and
922 plasma measurements. The multi-fluid model was able to reproduce Galileo
923 observations without the need of invoking a non-corotation component of the ambient
924 plasma flow, as required in the previous MHD modeling efforts (Kabin et al. 1999).
925 The model self-consistently yielded a total mass-loading rate of 5.4 kg/s for the
926 conditions of the E4 flyby, which is also in line with the two earlier Michigan-based
927 Europa MHD models.

928 ***3.1.2. Future Improvements in plasma/MHD models***

929 A detailed comparison among the models described in the previous paragraph is
930 presented in Table 2. Future improvements in modeling could take into consideration

931 the following suggestions.

932 *1. Include possible atmosphere asymmetries*

933 The Saur et al. and the Schilling et al. models describe the O₂ atmosphere with a
934 single scale height and assume a trailing leading asymmetry. Also in the MHD
935 models by Kabin et al. (1999), Liu et al. (2000), Rubin et al. (2015), the spatial
936 distribution of Europa's neutral atmosphere has been assumed as a relatively
937 simplified model. While these models use realistic atmospheric scale heights or/and
938 included asymmetries of the neutral density between the upstream and downstream
939 hemispheres due to ion-induced sputtering (Saur et al. 1998; Schilling et al. 2007;
940 Rubin et al. 2015), other potential asymmetries or inhomogeneities of Europa's
941 neutral atmosphere need to be considered in future simulations. For instance, the
942 recent model by Plainaki et al. (2013) suggested that Europa's exosphere could be
943 highly variable along its orbit around Jupiter depending on both the direction of the
944 incident plasma flow and the direction of solar illumination. The effects of the
945 variability of Europa's neutral atmosphere on its plasma interaction need to
946 investigated and quantified in future plasma modeling.

947 *2. Compute electron temperatures self-consistently*

948 The models by Schilling et al. (2007; 2008) do not compute the electron temperature
949 self-consistently in their model. Heat conduction along magnetic field lines from the
950 plasma torus reheat the newly ionized ions in the atmosphere. This mechanism is
951 extremely effective at Europa (Saur et al. 1998).

952 *3. Consider Europa's surface conductivity*

953 In the MHD models by Kabin et al. (1999), Liu et al. (2000), and Rubin et al. (2015),
954 the inner boundaries were all placed at the surface of Europa. While different
955 boundary conditions were adopted to represent the physical behavior of Europa's
956 surface in interacting with the surrounding plasma environment, such as absorbing
957 and fixed boundary conditions, the properties of Europa's interior were not modeled
958 directly. Given the presence of subsurface conducting layer that produces the
959 observed induced magnetic field at Europa, it is important for future MHD models to
960 directly take into account this aspect of the Europa interaction system. The concept of
961 virtual plasma in Schilling et al. (2007; 2008) is an approximate treatment of the non-
962 conductive surface of Europa and could modify the outcome of the simulations.
963 Duling et al. (2014) derived a consistent description of the inner boundary that takes

964 the non-conducting nature of the surface into account and could be implemented in
965 the Schilling et al. model. Approaches have been developed to incorporate interior
966 layers with different conductivities into global MHD models, and they have been
967 successfully applied to different planetary bodies including Io (Linker et al. 1998;
968 Khurana et al. 2011), Ganymede (Jia et al. 2009) and Mercury (Jia et al. 2015). Future
969 models of Europa's plasma environment may consider implementing such a capability
970 in order to more realistically simulate the effect of Europa's interior on its global
971 interaction.

972 **3.1.3. Physics-chemistry modeling**

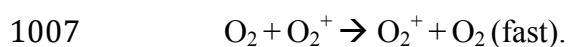
973 Dols et al. (2016) explored the "chemistry" of the Europa/magnetosphere interaction
974 focusing on the many reactions between ions, neutrals and electrons, many of which
975 are neglected by models described elsewhere in this paper. This 2D model, which was
976 adapted from Io simulations (Dols et al. 2008, 2012), follows a parcel of
977 magnetospheric plasma as it flows through Europa's atmosphere and tracks the
978 changes in mass and temperature for electrons and 7 ion species including heavy
979 magnetospheric ions (O^{n+} , S^{n+}) and pickup ions (H_2^+ , O_2^+). The density distributions
980 provided by the Dols et al. (2016) model give important information of the so called
981 "planetary ion environment" (or "ionized atmosphere") around Europa the
982 characteristics of which are directly related to the atmosphere properties. Given the
983 nature of the model itself, we do not in detail compare its parameters with the ones of
984 the plasma/MHD models in Table 2.

985 An analytic formula for the flow of an incompressible fluid around a perfectly
986 conducting cylinder was used to track plasma motion around the moon. This is a
987 simplification, but one that captures the basic features reported by other simulations
988 such as the slowing of plasma in front of the moon and speed-up at its flanks. For
989 atmospheric properties they used the 1D (radial) model of Smyth and Marconi (2006),
990 though the O_2 scale height and other properties were varied to explore the sensitivity
991 of the model. Upstream magnetospheric plasma conditions came from the recent
992 reanalysis of Galileo results by Bagenal et al. (2015).

993 Figure 19 shows the model's results for nominal magnetospheric conditions
994 (median magnetospheric plasma density and temperature as reported by Bagenal et al.
995 2015). The inflowing magnetospheric ions are mostly diverted around Europa and
996 their densities drop sharply due to loss by charge exchange with atmospheric neutrals.

997 The pickup ions flow close to the surface and form a dense, narrow wake in accord
998 with Galileo observations (Paterson et al. 1999). The average ion temperature
999 increases near the flanks, where the high plasma flow speed (about 200 km s⁻¹) results
1000 in energetic pickup ions.

1001 As the plasma flows through the atmosphere the model also keeps track of the
1002 various processes acting upon the neutrals. Dols et al. (2016) assume a scale height of
1003 the O₂ atmosphere of 150 km, which assumes it originates entirely from sputtering.
1004 However, the main fraction of the O₂ atmosphere will be thermally accommodated
1005 with the surface and resulting in a much lower scale height. The authors find a large
1006 O₂ sink due to symmetric charge exchange:



1008 This results in the loss of an atmospheric molecule, which either escapes Europa's
1009 gravity or impacts the surface. The newly-ionized O₂ is not, as commonly assumed in
1010 atmospheric models, immediately lost to the magnetosphere: the pickup ion continues
1011 through the atmosphere and becomes the seed of a cascade of charge exchange
1012 reactions with other atmospheric O₂ molecules. This continues until the plasma parcel
1013 is convected out of the atmosphere. Of course, these ions can only be contained in the
1014 atmosphere because it is thick enough to provide enough ion-neutral collisions. With
1015 a realistic scale height of the O₂ atmosphere the evacuation of the newly-ionized O₂
1016 the magnetospheric plasma would be much more effective.

1017 Based on these simulation Dols et al. (2016) concluded that this loss process
1018 dominates, by a factor of 4 to 40 depending on the simulation parameters used, over
1019 the second fastest loss process of electron-impact ionization. This is in accord with the
1020 modeling of Saur et al. (1998), whose "atmospheric sputtering" process is broadly
1021 similar to the mechanism outlined above. The O₂ loss rates calculated by Saur et al.
1022 (1998) also agree quantitatively with Dols et al. (2016) despite very different
1023 modeling approaches and assumptions. The result seems to be consistent with other
1024 Europa plasma models as well (e.g., Kabin et al. 1999; Schilling et al. 2008), but
1025 those papers did not discuss O₂ loss rates explicitly.

1026 This symmetric charge exchange loss process has not been considered by
1027 atmospheric modelers, which commonly assume that electron-impact ionization,
1028 followed closely by electron-impact dissociation, are the dominant loss processes for
1029 O₂. This presents an interesting problem for the atmospheric modeling community:
1030 their loss rates seem to be underestimated by an order of magnitude, while at the same

1031 time they may have *overestimated* the O₂ source rates (via sputtering) by neglecting
1032 the plasma flow diversion found by all Europa plasma modelers.

1033 Another consequence of this symmetric charge exchange cascade is the
1034 production of a Jovian neutral O₂ torus. Dols et al. (2016) estimated that the fast
1035 neutral O₂ leave the charge exchange reaction at an average speed of $\sim 5 \text{ km s}^{-1}$, and at
1036 a rate on the order of 100 kg s^{-1} . This is fast enough to escape Europa's gravity and
1037 form a broad, and fairly dense, torus around Jupiter. Such a neutral torus could help to
1038 explain ambiguous detections of a neutral cloud in the vicinity of Europa's orbit.

1039 ***3.1.4 Charged Energetic Particles***

1040 The radiation environment of Europa is believed to play a role in the weathering of
1041 the surface and in the modifications of the atmosphere. Energetic charged particles
1042 are generally not impeded by the electromagnetic fields near the body, such as the
1043 magnetic induction effect at high magnetic latitudes, so can pass directly into the ice.
1044 Electrons that enter the ice can deposit energy to $> \text{cm}$ depths and physically alter the
1045 ice and non-ice materials that are present. For example, they can change the thermal
1046 conductivity (Howett et al. 2011) or lattice structure (Hansen and McCord 2004) of
1047 the ice. Energetic electron and ion precipitation can lead to the manufacture of new
1048 materials in the ice such as peroxide (Loeffler et al. 2006). Volatile atoms and
1049 molecules created in this way can escape from the ice into the atmosphere.

1050 Suprathermal to energetic ions can also modify the ice lattice. In addition,
1051 they sputter the ice surface, leading to the creation of newly liberated neutrals.
1052 Cassidy et al. (2013) estimated the global sputtering rate of Europa and found 2×10^{27}
1053 water molecules per s are created, some of which leave the surface as molecular
1054 hydrogen and oxygen. These ions can also interact with bound atmospheric neutrals
1055 and liberate them into circumplanetary or other orbits. The putative neutral gas torus
1056 at Europa's radial distance (e.g., Lagg et al. 2003; Mauk et al. 2004; Kollmann et al.
1057 2016) may be supplied by this interaction between Jovian ions and bound atmospheric
1058 neutrals.

1059

1060 **3.2. Comparison of atmospheric models and main improvements required**

1061 It is a wide consensus that Jupiter's magnetospheric plasma environment is the main
1062 agent for the generation of Europa's tenuous atmosphere. Several models based on
1063 very different approaches have been developed to describe the tenuous atmosphere of

1064 this moon and to better constrain its generation processes. Shematovich et al. (2005)
1065 and Smyth and Marconi (2006) used a Monte Carlo multispecies approach to derive
1066 the atmospheric O₂, H₂O, H₂, and H, O and OH spatial structure. Cassidy et al. (2007)
1067 explored the hypothesis of O₂ surface reactivity and Leblanc et al. (2002; 2005) and
1068 Cassidy (2008) studied the structure and evolution of sputtered exospheric trace
1069 species using Monte Carlo models. Plainaki et al. (2010; 2012) incorporated
1070 sputtering and radiation chemistry information derived from laboratory measurements
1071 (Famà et al. 2008; Teolis et al. 2009) into European exospheric models, in order to
1072 quantify the neutral particle release and to estimate its longitudinal dependence.
1073 Considering the O₂ tenuous atmosphere, the study was extended to provide
1074 information on the morphology of the environment at different phases of Europa's
1075 orbit around Jupiter (Milillo et al. 2016; Plainaki et al. 2013).

1076 In Table 3 and Table 4 we summarize the main characteristics of some of the
1077 most recent atmospheric models for Europa, in means of model assumptions and main
1078 outputs, respectively. In Section 3.2.1 we will discuss the available techniques applied
1079 to existing models whereas in Section 3.2.2 we will make an analytical comparison of
1080 some of the existing models on the basis of the parameters presented in Table 3 and
1081 Table 4.

1082 ***3.2.1. Current Modeling Techniques and Assumptions***

1083 In the low Knudsen-number atmosphere of Europa (see Figure 1) collision times
1084 between molecular species become long compared to transport times and modeling
1085 the physics and chemistry imposes some basic assumptions on the environment
1086 properties. To describe Europa's thin gas environment, two basic modeling techniques
1087 have been proposed in literature based either on the direct solution of the Boltzmann
1088 equation or on the discrete modeling of numerous particles by means of Newton's
1089 laws of classical dynamics.

1090 Since there is no general analytical approach to solving the Boltzmann
1091 equation, kinetic models are based on the use of numerical methods. The gas flow in
1092 the near-surface atmosphere, i.e., in the Knudsen layer and the transition region
1093 between collision-dominated and collisionless atmospheric regions (see Figure 1), is
1094 best described by a system of the kinetic Boltzmann equations, because of the non-
1095 thermal source terms due to both surface sputtering and charge-exchange by the
1096 magnetospheric plasma inflow (Shematovich et al. 2005). Such highly non-

1097 equilibrium systems are difficult to analyze because of the mathematical complexity
1098 of the Boltzmann kinetic equations (nonlinearity and high multiplicity of the collision
1099 integrals), requiring new and sophisticated approaches in the field of rarefied gas
1100 dynamics.

1101 A very promising approach to study such kinetic systems is the development
1102 of discrete mathematical models that use the probabilistic interpretation of collisions
1103 in an ensemble of model particles. The DSMC method (Bird, 1994) and its
1104 modification for studying non-equilibrium processes in the planetary atmospheres
1105 (Marov et al. 1996; Shematovich, 2004) belong to this class of approaches. A
1106 stochastic discrete model to investigate the formation, kinetics, and transport of
1107 suprathermal particles in the near-surface atmosphere of Europa should take into
1108 account the following peculiarities of the atmospheric gas flow: *(i)* the local mean free
1109 time and path for suprathermal particles ejected from the icy surface and subsequently
1110 dissociated/ionized by the magnetospheric plasma electrons and ions, should be
1111 considered, respectively, as the characteristic time and space scale describing the gas
1112 state; *(ii)* the parameters of the atmospheric gas change strongly from the collision-
1113 dominated regime of gas flow in the Knudsen layer to the virtually collisionless (free-
1114 molecule) regime of flow in the exosphere; *(iii)* significant differences between the
1115 densities of the suprathermal particles and the ambient atmospheric gas are commonly
1116 observed. Therefore, in the numerical models of the near-surface atmosphere, the
1117 following approaches must be followed: *(i)* splitting of the solution of the basic
1118 kinetic system into simulation steps considering for the suprathermal particle sources
1119 collisional thermalization and free molecular transport on a discrete time scale; *(ii)*
1120 stochastic simulation of the formation of suprathermal particles and their local
1121 kinetics by using analogue Monte Carlo algorithms with statistical weights; *(iii)*
1122 calculation of the trajectories of suprathermal particles in the whole exosphere by
1123 using finite-difference algorithms.

1124 The direct methods of solving the stochastic (master) kinetic equation consist
1125 in setting up and solving a system of equations for the probabilities of all possible
1126 paths of the state of a chemically reactive rarefied gas. Unfortunately, this direct
1127 procedure can be performed only for a few very simple chemical systems (Van
1128 Kampen, 1984) and involves enormous computational difficulties for real systems of
1129 chemical reactions. The kinetic Monte Carlo method (see, e.g., Marov et al. 1996;

1130 Shematovich, 2004), which consists in generating a sample of paths for the state of a
1131 chemically reactive gas, is an efficient tool for studying complex kinetic systems in
1132 the stochastic approximation. The path generation procedure is much simpler - a
1133 sequence of transitions between the states of a chemically reactive gas and transition-
1134 separating times should be drawn based on the proper probability distributions. Such
1135 procedure is an analogue Monte Carlo algorithm for solving the stochastic kinetic
1136 equation. In the numerical realizations of the kinetic model the following recent
1137 developments in the theory and practice of DSMC method were used (see, e.g.
1138 Shematovich 2004; Shematovich et al. 2015): (i) an effective approximation of the
1139 major frequency, where the collision probability for the chosen pair is estimated from
1140 the maximum possible frequencies and is used in choosing the next transition; (ii) the
1141 multichannel nature of the selected reaction is taken into account for the transition to
1142 be realized; this means that the transition is treated as the simultaneous drawing of all
1143 possible (elastic, inelastic, and chemically reactive) channels for each one of which
1144 the corresponding weight is transferred to the total cross section of the collisional
1145 process, proportionally to the ratio of the partial cross section for the given channel;
1146 (iii) since the algorithmic steps of throwing in suprathermal particles, in accordance
1147 with the source functions, and drawing the collisional transitions are accompanied by
1148 the formation of new model particles, it is necessary to control the total number of
1149 model particles in the numerical model. An efficient method for this control is the so-
1150 called clustering of model particles, where groups of model particles with similar
1151 parameters are combined into a single particle with weighted parameters.

1152 Test particle Monte Carlo models can be considered as a sub-family of the
1153 DSMC models in which the collisions are not considered. Usually each test particle is
1154 placed at a random location, e.g. in a cell representing a region of Europa's surface,
1155 and is given a random velocity and angular distribution, selected on the basis of the
1156 population properties (e.g. species, velocities) and the physical process in action (e.g.
1157 surface sputtering, radiolysis, etc.). Then the particle trajectories are integrated taking
1158 into account, in general, the gravitational fields of both Europa and Jupiter, as well as
1159 Europa's rotation. The integration time step can be set equal to $dt = \frac{dx}{vn_c}$ where n_c is
1160 the number of particles inside the cell, and v is the velocity of the emerging particle
1161 and dx is the dimension of each cell.

1162 **3.2.2. Differences in the implementation**

1163 Most models agree that the H₂O, H₂ and O₂ atmospheres of Europa are created by ion
1164 bombardment of the surface plus possible contributions from plumes and sublimation.

1165 Ip (1996) proposed a model for the atmosphere of Europa based on the
1166 sputtering rates estimated for the case of icy surfaces (Shi et al. 1995) assuming a
1167 simple model for the plasma effects. The atmosphere was considered to be globally
1168 homogeneous with respect to surface sources.

1169 The 1-D kinetic model of Shematovich and Johnson (2001) for O₂ and the
1170 improved 1-D kinetic model of Shematovich et al. (2005) for both O₂ and H₂O
1171 provided the velocity distribution for these species in the near-surface region. These
1172 models were the first kinetic models of Europa's near-surface atmosphere with
1173 collisions. In the 1D kinetic model of Shematovich and Johnson (2001), the following
1174 physical processes were taken into account: a) collisions between all atmospheric
1175 species in the near-surface (Knudsen) layer; b) O₂ dissociation by solar UV-photons
1176 and by magnetospheric electrons; c) charge-exchange (often referred to as
1177 atmospheric sputtering) between neutrals and plasma ions; d) adsorption; e)
1178 thermalization; f) rapid desorption in the collisions of O₂ molecules with Europa's icy
1179 surface. The stochastic version (Marov et al. 1996) of the DSMC method was used in
1180 a one-dimensional approximation to calculate the chemical and thermal structure of
1181 the atmosphere and the production rate of oxygen atoms in the reactions of
1182 dissociation of the parent molecule O₂, ejected into the atmosphere upon radiolysis of
1183 the moon's icy surface. It was shown that the primary loss process of oxygen is its
1184 ionization by the magnetospheric electrons and the secondary loss process is atomic
1185 oxygen escape. The latter provides an important source of neutral gas to the neutral
1186 torus forming along the satellite's orbit. A modified model was further developed
1187 (Shematovich et al. 2005; Shematovich, 2006) to study the formation of both the near-
1188 surface atmosphere and hot oxygen corona induced by the thermal and nonthermal
1189 sources of atoms and molecules due to the radiolysis of Europa's icy surface. The
1190 dissociation and ionization of parent H₂O and O₂ molecules by magnetospheric
1191 electrons and solar UV-radiation as well as the charge-exchange between vapour
1192 molecules (water and oxygen) and low-energy magnetospheric ions, were considered
1193 in that model. The spatial distribution of the near-surface neutral atmosphere and its
1194 thermal structure were calculated. It was shown that oxygen molecules predominantly

1195 populate the near-surface atmosphere which is surrounded by an extended and
1196 rarefied hot corona of atomic oxygen (see Figure 20).

1197 The estimated O₂ atmosphere scale was of the order of ~20 km at small
1198 altitudes; the energy distribution of O₂ is thermal with a high-energy tail. Nagy et al.
1199 (1998) had previously noted that Europa must have a corona of hot atomic oxygen
1200 formed in the dissociative recombination reaction of the molecular ion O₂⁺ with
1201 ionospheric electrons. The observations by *Cassini* during the flyby of the Jovian
1202 system (Hansen et al. 2004) showed that the atomic oxygen population is more widely
1203 distributed in the exosphere of Europa compared to the predominantly near-surface O₂
1204 distribution predicted by the models by Shematovich et al. (2005) and Shematovich
1205 (2006).

1206 Interestingly, the O₂ scale height of about 20 km in the model by Shematovich
1207 et al. (2005), is consistent with a gas in thermal equilibrium with Europa's ~100 K
1208 surface. This suggests that the plasma impingement on the atmosphere does little to
1209 heat the bulk of the atmosphere and the magnetospheric ions pass the thin atmosphere
1210 mostly unaffected. This may be at odds with observations, such as those by Kliore et
1211 al. (1997) of an ionosphere with a scale height one order of magnitude larger, or the
1212 Roth et al. (2016) vertical profiles of atmospheric emission likewise suggestive of
1213 scale heights much larger than 20 km. Addressing these discrepancies requires
1214 modeling both the ionosphere and atmosphere self consistently, something that has
1215 not been attempted yet.

1216 The kinetic model by Smyth and Marconi (2006) includes all the water group
1217 species, namely H₂O, H₂, O₂, OH, O, and H. The results of this model showed that O₂
1218 is the dominant species near the surface while H₂ is somewhat less abundant but is the
1219 dominant species at higher altitudes and has by far the largest escape rate. In this
1220 model, the heavy O₂ molecule is lost from the atmosphere either as hot O generated by
1221 the electron impact and ion-collisional dissociation of O₂ or as O₂⁺ generated through
1222 electron impact ionization of O₂ (direct ion sweeping). The model predicts that the
1223 escaping O atoms have velocities near the escape velocity (equal to 2.02 km/s) and
1224 therefore they are expected to be distributed near Europa's orbit and to form an
1225 important gas torus. Due to its small mass, H₂ escapes easily the moon's gravity and,
1226 similarly to the O case, is distributed around the moon near its orbit forming a gas
1227 torus. One part of the H₂ population is also lost as hot H generated through electron

1228 impact dissociation. These H atoms are distributed over a large volume of the Jupiter
1229 system. The model by Smyth and Marconi (2006) predicts for the rest of the
1230 atmospheric species column abundances much smaller (by an order of magnitude)
1231 than the one of H₂. It is evidenced that in the model by Smyth and Marconi (2006)
1232 shows that the assumed atmospheric source rates for the various species are
1233 determined by partitioning the O₂ source rate, the value of which is chosen so as to
1234 reproduce the O UV brightness reported by Hall et al. (1995) using the electron-
1235 impact excitation cross-sections of Kanik et al. (2003).

1236 The collisionless model by the University of Bern was originally developed
1237 for Mercury's exosphere (Wurz and Lammer, 2003; Wurz et al. 2010) and extended
1238 for the Moon (Wurz et al. 2007). It has been used for many planetary objects, most
1239 recently also for the icy moons of Jupiter (Wurz et al. 2014; Vorburget al. 2015).
1240 The model is a Monte Carlo calculation of a collisionless neutral environment (often
1241 referred to as an exosphere). Particles are released either from the surface or from the
1242 exobase through several release processes: thermal release, sublimation, photo-
1243 stimulated desorption, micro-meteorite impact vaporization, and sputtering. For the
1244 latter, sputtering of ice and minerals are treated differently. For each release process
1245 the 3D velocity distribution at the surface is considered. Trajectories are calculated in
1246 2D by using Kepler's laws. Modifications to the trajectory for photon pressure are
1247 performed where necessary, e.g. for Na. Ionization and fragmentation of molecules
1248 along the trajectory are calculated using ionization and fragmentation rates for
1249 photons and electrons for the Jupiter system. Released particle fluxes from the surface
1250 are calculated ab initio, e.g. by using the chemical and mineralogical composition of
1251 the surface and applying the physical laws of particle removal for the different release
1252 processes. Recently, Vorburget al. (2015) presented a similar model for Callisto's
1253 exosphere. The main outputs of the code are density profiles, radial and transverse
1254 column densities, for all species and release processes. In addition, velocity
1255 distributions at a certain altitude, loss rates, escape fluxes are also provided.

1256 The Europa Global model of Exospheric Outgoing Neutrals (EGEON) is a
1257 numerical single-particle Monte Carlo model simulating the generation of Europa's
1258 neutral atmosphere (Plainaki et al. 2010; 2012; 2013; Milillo et al. 2016). As physical
1259 sources the model includes ion sputtering and radiolysis and as loss processes, the
1260 sticking to the surface capability of the H₂O molecules, the electron-impact ionization

1261 and the gravitational escape for all the considered species (H_2O , O_2 , H_2). The source
1262 rates used as an input in EGEON were calculated on the basis of the known Jupiter's
1263 magnetospheric energy spectrum of ions (Paranicas et al. 2002), the literature
1264 sputtering yields (Famá et al. 2008) and the moon's surface temperature map (Spencer
1265 et al. 1999). The resulting atmospheric density was compared, a posteriori, to the
1266 observations (where existent) in order to validate the model. This particular approach
1267 provided an opportunity to discuss aspects of sputtering and radiolysis modeling that
1268 had not been in detail treated in detail in the past. For example, using the precise
1269 formula for the sputtering yield of Famá et al. (2008), the different release
1270 mechanisms leading to the generation of the moon's exosphere were distinguished,
1271 and, their dependence on the specific properties of the impacting ions (e.g. species,
1272 energy) and on the icy surface temperature was attributed. As a main output, EGEON
1273 provides the 3-D density distribution of the main atmospheric constituents (i.e. the
1274 radiolytically produced H_2 and O_2 and the sputtered H_2O , see Figure 21). The
1275 possibility to estimate these distributions for different orbital phases also exists in
1276 EGEON. Milillo et al. (2016) used the EGEON densities to define a parameterized
1277 equation giving the O_2 density as a function of altitude, latitude and longitude at
1278 different orbital positions of Europa. This analytical model for the tenuous O_2
1279 atmosphere is proposed as a tool for the interpretation of future observations to be
1280 performed either with JUICE payload instruments or with space telescopes (Milillo et
1281 al. 2016). In Figure 22, we show the expected O_2 density distribution at different
1282 orbital phases. It is evidenced that at low altitudes (i.e. below ~ 150 km), no detailed
1283 (but only integrated) information on the density distribution can be extracted from
1284 EGEON due to the model's spatial resolution ($\sim 0.1 R_E$). Moreover, EGEON allows
1285 investigating the trailing/leading and sunlit/dark hemisphere asymmetries and the
1286 escape rate from the moon as a function of the surface release mechanisms. Recently,
1287 the model results were used for the interpretation of the first observations of the
1288 Europa plumes (Roth et al. 2014b).

1289 Cassidy et al. (2007, 2008, 2009) used a collisionless atmospheric model to
1290 simulate the O_2 atmosphere (2007), Na exosphere (2008), and trace species (2009)
1291 such as CO_2 and SO_2 . The first of these models explored the sensitivity of the
1292 atmosphere to surface reactivity, which was later found to be important to the O_2 and
1293 CO_2 exospheres of Saturn's icy moons (Teolis et al. 2016). The 2008 paper concluded

1294 that visible emissions from Europa in eclipse observed by Cassini are likely from
1295 electronic excitation of atomic sodium. Both papers proposed hypotheses to explain
1296 the non-uniformity of photon emissions from the atmosphere, but further observations
1297 (Roth et al. 2016) show that the emission patterns are not explained by any published
1298 model. The implementation of Cassidy's model was kept as simple as possible. As
1299 with many other atmospheric models, there was little consideration for plasma
1300 physics: the electron-impact ionization lifetime, for example, was a constant despite
1301 the variable electron temperatures and densities (see Section 3.1). It also, along with
1302 other atmospheric models, did not consider a possible major loss process identified by
1303 Dols et al. (2016).

1304 Sputtering due to surface bombardment by magnetospheric ions represents
1305 only one of the exogenic processes influencing the generation of Europa's
1306 atmosphere. Both the kinetic models by Shematovich et al. (2005) and Smyth and
1307 Marconi (2006) provided important results based on the chemistry between the
1308 various atmospheric constituents in the first atmospheric layers near the surface. Both
1309 of these models do not consider different configurations between Jupiter, Europa and
1310 the Sun (corresponding to different orbital phases) and the effect that they could have
1311 on the atmosphere's spatial distribution and the escape rate of the neutral particles. To
1312 account for such a possible effect, Plainaki et al. (2013) applied the EGEON model
1313 for different configurations between the moon, Jupiter and the Sun and investigated
1314 the trailing/leading and sunlit/dark hemisphere asymmetries in the spatial distribution
1315 of the atmosphere O₂ density. They showed that the O₂ atmosphere is explicitly time-
1316 variable due to the time-varying relative orientations of solar illumination and the
1317 incident plasma direction (see Figure 22). Solar illumination of Europa by the Sun and
1318 preferable plasma impact direction together are the key agents determining the spatial
1319 distribution of the generated O₂ exosphere and the O₂ release efficiency. The density
1320 of the released O₂ molecules becomes maximal when the trailing hemisphere
1321 coincides is sunlit resulting in a surface density of $\sim 10^{14} \text{ m}^{-3}$ (Plainaki et al. 2013,
1322 yields review (Milillo et al. 2016) included). The EGEON results on the O₂ column
1323 densities were consistent with the surplus of OI emission at the 90° west longitude
1324 (leading hemisphere) observed by HST (Saur et al. 2011). According to EGEON,
1325 solar illumination prevails over the more intense bombardment of the trailing
1326 hemisphere by energetic ions in determining the efficiency of the O₂ release. The

1327 escape rate from the moon of O-atoms produced by the dissociation of exospheric O₂
1328 molecules was maximal when trailing hemisphere coincides with sunlit hemisphere.
1329 In this case, the rate of supply of O-atoms to the torus is estimated to be 2.1 10²⁵/s
1330 (Plainaki et al. 2013, yields review included). Although the O₂ column density
1331 calculated with EGEON was, in general, consistent with the observations of the OI
1332 emission from the trailing hemisphere of Europa, the longitudinal asymmetry (at 230–
1333 250° west longitude) was not reproduced by the model. Such asymmetry, however,
1334 was re-produced in the model by Cassidy et al. (2017), allowing O₂ molecules to react
1335 with Europa's visibly dark surface material and assuming at the same time a uniform
1336 electron excitation of O₂ over the trailing hemisphere.

1337 One of the most important differences among the existing Europa's
1338 atmosphere models is the considered pattern for the plasma ion precipitation to the
1339 moon's icy surface. This is a fundamental point in modeling that determines
1340 significantly the properties of the generated neutral environment. Since the ejection of
1341 surface material due to the impact of magnetospheric ions to Europa's icy surface is
1342 the dominant agent for the release of both sputtered and radiolytical products, the
1343 considered ion precipitation pattern becomes a critical parameter for each model.
1344 Pospieszalska and Johnson (1989) were the first to estimate the ion bombardment
1345 pattern. Specifically, Pospieszalska and Johnson (1989) showed that 30 keV sulphur
1346 ions from Jupiter's magnetosphere can eventually reach almost all points on the
1347 satellite surface and result in a near linear angle-dependence of the relative ion flux,
1348 with the maximum flux at the trailing hemisphere apex and with the minimum at the
1349 opposite point (180°). Cassidy et al. (2007) and Plainaki et al. (2012) considered a
1350 preferential neutral ejection from the trailing hemisphere, using a similar exit-angle
1351 distribution as the one proposed by Pospieszalska and Johnson (1989), that is a cosine
1352 flux on the trailing hemisphere due to either the corotating plasma or hot electrons.
1353 Paranicas et al. (2001) showed also that most energetic electrons impact Europa's
1354 trailing hemisphere, primarily at low latitudes. Subsequent estimations on the
1355 magnetiospheric ion flux by Paranicas et al. (2002) based on information obtained
1356 with Galileo were taken as a proxy for sputtering rate (e.g., Tiscareno and Geissler
1357 2003; Cassidy et al. 2008). However, Cassidy et al. (2013) argued that that ion flux
1358 and sputtering rate are quite distinct. In particular, Cassidy et al. (2013) discussed the
1359 ion motion at Europa's environment and distinguished the effect of different ion

1360 energies on the ion bombardment patterns. They showed that at the typical energy of
1361 the cold ion population (~ 100 eV), sulphur ions have very small gyroradii and the ion
1362 speed is small compared to the corotation drift speed. The corotation drift carries the
1363 ions onto the trailing hemisphere, resulting in the bullseye pattern centered on the
1364 trailing apex (see Cassidy et al. (2013), Fig. 8, upper left). A similar bullseye pattern
1365 found in the UV surface reflectance was attributed to absorption by SO_2 in the surface
1366 (Hendrix et al. 2011). At higher ion energies (10^3 eV), the ion speed becomes
1367 comparable to the corotation drift speed, though the gyroradii are still small compared
1368 to Europa's radius. With increasing ion speed the corotation drift remains unchanged
1369 hence the average ion speed in the corotation direction remains unchanged too. The
1370 ion motion parallel to the magnetic field faces is not influenced and at high energies
1371 the ions increasingly reach Europa's surface from the North or South. As a result, at
1372 even higher energies ($\sim 10^5$ eV), the precipitating ion flux peaks at the poles whereas
1373 at $\sim 10^6$ eV the gyroradius is comparable to Europa's radius and the ions can access
1374 Europa's surface from all directions.

1375 Considering the plasma flow diversion, the existing models of the
1376 magnetosphere-moon interaction have generally assumed either the atmosphere-
1377 centric approach or the plasma-centric approach. The atmosphere-centric approach
1378 calculates ion fluxes by treating Europa as electromagnetically inert. The modelers
1379 assume that Europa's interaction is lunar-like, that is a completely absorbing barrier.
1380 However, this is not consistent with the observations (Paranicas et al. 1998; Paterson
1381 et al. 1999) that show plasma diversion around Europa as a consequence of mass
1382 loading and ionospheric conductivity (Saur et al. 1998). To address the balance
1383 between mass loading and loss, realistic scale heights for the different exospheric
1384 species should be identified. The plasma-centric approach assumes a static
1385 atmosphere that diverts the plasma flow around Europa. According to these models
1386 plasma has limited access to Europa's surface. The shortcoming in this approach is
1387 that it neglects to consider self-consistency.

1388 Figure 23 shows the O_2 source rates from the literature going back to the first
1389 estimate by Johnson et al. (1982). There is a big discrepancy among the results of
1390 different models because of the different assumptions and parameters that go into
1391 such models (see Table 3). The differences can be ascribed to a number of key
1392 assumptions that differ from paper to paper. One such assumption is the choice of

1393 charged particle population responsible for radiolysis and sputtering (indicated by
1394 colors in Figure 23). The particles bombarding the surface range from thermal plasma
1395 (eV-keV) to energetic non-thermal (keV-MeV) populations and include electrons,
1396 protons, oxygen and sulphur ions of a variety of charge states. The surface is also
1397 bombarded by pickup ions (primarily O_2^+) from the atmosphere (Ip, 1996; Rubin et al.
1398 2015) and energetic neutral O_2 (Dols et al. 2016). The bombarding flux, bombardment
1399 pattern, and sputtering yields all vary as a function of species and energy (e.g.,
1400 Cassidy et al. 2013; Galli et al. 2016) and models generally do not include all of these
1401 species and energies. Eviatar et al. (1985), for example, only considered O_2
1402 production by low-energy thermal plasma ions, while Cooper et al. (2001) only
1403 considered energetic non-thermal electrons and ions. Neither paper includes a
1404 justification for these assumptions. The lack of agreement on this matter is the main
1405 reason for the range of results shown in Figure 23.

1406 Loss processes are another source of disagreement. All models agree, roughly,
1407 on the electron-impact loss process rates (see summary in Johnson et al. 2009). But
1408 many plasma simulation models include a loss process left out of the atmospheric
1409 models: charge exchange between atmospheric O_2 and the pickup ion O_2^+ , that is a
1410 cascade of symmetrical charge exchanges between O_2^+ ions and neutral O_2 . This
1411 mechanism takes place because once an atmospheric oxygen molecule is ionized by
1412 an electron or photon it is first picked up by the flow and entrained through the
1413 atmosphere. A cascade of symmetrical charge exchanges with other atmospheric O_2
1414 neutrals along the whole path of the flow through the atmosphere takes place (Dols et
1415 al. 2016). Each charge exchange ejects a fast neutral until the ultimate ion is
1416 eventually convected out of the atmosphere. This process was firstly identified as a
1417 major loss process by Saur et al. (1998), who called it “atmospheric sputtering”.
1418 Kinetic models (e.g. Shematovich et al. (2005)) have indeed included its effects by
1419 considering a constant rate for the respective reaction. More recently Lucchetti et al.
1420 (2016) examined the effects of the consideration of such a loss process in atmosphere
1421 modeling. Dols et al. (2016) showed that the total production rate of ejected neutrals
1422 could be an order of magnitude larger than the production of ions. To address the
1423 relative weight of each loss process, the identification of a realistic scale height of O_2
1424 is necessary.

1425 The energy distribution of each atmospheric constituent is an important
1426 parameter of the Europa atmosphere models. The assumptions used in modeling are in
1427 principle based on the existing laboratory measurements though the conditions at the
1428 moon's surface may differ significantly. Single particle Monte Carlo models assume
1429 standard energy distribution functions describing the respective release process (e.g.
1430 sputtering, sublimation). On the contrary, DSMC models estimate dynamically the
1431 energy distribution function of the atmosphere dynamically as at each simulation step
1432 collisions and chemical reactions change the energetics of the molecules.

1433 **3.3. Definition of a global unified model of Europa's atmosphere**

1434 A global model of Europa's tenuous atmosphere should take into account the
1435 following important physical properties.

1436 *1. Position of Europa with respect to Jupiter's plasma sheet*

1437 Due to the tilt of Jupiter's magnetic field relative to Europa's orbit plane, the plasma
1438 environment changes as the dipole spins. The cold plasma density maximizes at the
1439 'centrifugal equator', the equilibrium surface lying between the magnetic equator and
1440 the rotational equator. However, as Europa orbits around Jupiter it moves above and
1441 below this plane by ~ 1 Jupiter radius (R_J). The cold plasma decreases in density as
1442 $\exp(-(z/H)^2)$ above the centrifugal equator with a scale height of $H \sim 1 R_J$ (Bagenal,
1443 1994), resulting in an average cold ion density of 0.75 times the centrifugal value
1444 above (Cassidy et al. 2013). The hot ions do not decrease much in density above the
1445 centrifugal equator owing to their uniform pitch angle distribution (Roederer, 1970).
1446 In a global atmosphere model, a plasma model considering different conditions of the
1447 Jupiter plasma sheet, such as the one by Bagenal et al. (2015), should be taken into
1448 account. We note that the consideration of a plasma model embedded in the
1449 atmosphere model is necessary for constraining both primary (see Cassidy et al. 2013)
1450 sources and secondary (see Saur et al. (1998)) sources and losses (see Dols et al.
1451 (2016); Lucchetti et al. (2016)) of the atmosphere.

1452 *2. Ion precipitation to the surface*

1453 The spatial density and energy distribution of Europa's tenuous atmosphere is likely
1454 conditioned from the properties of the magnetospheric ion precipitation to the surface.
1455 The critical parameter determining the efficiency of the release of material at each
1456 surface point (characterized by a specific surface temperature) is the product of the
1457 intensity of the ion flux energy spectrum at a specific energy with the release yield

1458 (for this ion energy). In a global atmosphere model, the ion precipitation patterns at
1459 different energies should be taken into account in such an estimation. An overall
1460 release taking into consideration both the directional properties of the ion impact and
1461 the actual efficiency of the release of surface material integrated in ion energy should
1462 be estimated. This consideration is particularly important for the atmosphere
1463 constituents generated through direct sputtering (e.g. H₂O) and with small probability
1464 of multiple bouncing on ice (i.e. sticking~1).

1465 *3. Release processes and yields*

1466 A spatially-dependent calculation of Europa's sputtered and radiolytically produced
1467 atmosphere should be based on the use of up-to-date plasma parameters and
1468 sputtering yields. The effect of both hot and cold ion populations on the surface
1469 material release should be estimated independently. Possible dependence of the
1470 sputtering rate on the regolith grain size as argued by Cassidy et al. (2013) should be
1471 examined too.

1472 Knowledge of the physics of ice in the high radiation environment of Europa
1473 is a major component in understanding both the surface composition of this moon and
1474 the release of material to its tenuous atmosphere. Decades of laboratory
1475 experimentation on water ice, aimed at providing such knowledge, have now enabled
1476 a comprehensive, self-consistent and quantitative model for the yields of the major
1477 radiolysis products: O₂, H₂ and H₂O₂. Recent work by Teolis et al. (2017) revealed an
1478 inverse projectile range dependence in the yields (per unit deposited energy) of O₂ and
1479 H₂ from ice, but not in H₂O₂. This result suggests - unlike H₂O₂ which may be
1480 synthesized by hydroxyl reactions all along the particle tracks as they penetrate into
1481 the solid - that O₂ and H₂ are generated preferentially at the ice surface in an atomic
1482 scale layer ~30 Å in thickness. Preferential hydrogen escape from the surface-layer
1483 oxygenates the surface stoichiometry, altering the chemical pathways in favor of the
1484 formation of O₂ over H₂O₂. The analytical expressions approximating the energy and
1485 temperature dependence of the radiolysis yields, enabling accurate estimates of
1486 equilibrium H₂O₂ abundances in the surfaces, and sputtered source rates of H₂ and O₂
1487 into the tenuous atmospheres, are fundamental components of future models of
1488 Europa's neutral environment. The applicability of these to Europa's icy surface is
1489 contingent on surface impurity concentrations, depending on the endogenic surface
1490 composition, and the degree of preferential sputtering, escape, and fallback of

1491 sputtered or cryovolcanic water vapor. Therefore, the future modeling efforts should
1492 take into account the constraints in the efficiency of surface release dependent on the
1493 abundance of surface impurities.

1494 Water ice sublimation should be examined through the consideration of
1495 different surface composition patterns including impurities that can significantly
1496 diminish the efficiency of this mechanism. In addition, possible thermal anomalies on
1497 the surface should be incorporated in such estimations in order to define realistic rates
1498 of sublimated water outgassing at different surface points and during different moon
1499 orbital phases.

1500 Moreover, the role of micrometeoroid impact vaporization as well as plume
1501 outgassing should be evaluated in more detail in the future with the scope to provide
1502 an upper limit in the atmosphere surplus due to these transient source process.

1503 *3. Particle re-impact to the surface*

1504 Considering the particle re-impact to the ice, the following considerations should be
1505 taken into account in a global model:

- 1506 • sticking and thermal accommodation based on the properties of each particle
1507 species;
- 1508 • gas diffusion through the porous regolith;
- 1509 • cold trapping near the poles;

1510 *4. Particle circulation, interactions and loss*

1511 In the near-surface Knudsen layer, collisions and plasma ion chemistry should be
1512 taken into account in a global model. In an ideal case, the reaction cross sections
1513 considered in the model should be energy dependent, although such an assumption
1514 would require much longer calculation times. A collisionless approach can be
1515 assumed at regions where $Kn > 1$. The modeling of the plasma flow around Europa is
1516 another important parameter determining the characteristics of the loss processes.
1517 Simplified approaches including the description of the flow as an incompressible flow
1518 around a conducting obstacle should be replaced by more accurate ones requiring the
1519 use, at least in the form of input, of quantities derived directly from MHD models
1520 (e.g. plasma energy and density at the borders of the atmosphere simulation box).

1521 Finally, a three-dimensional model including all the water group species (e.g.
1522 H_2O , H_2 , O_2 , OH , O , H , H_2O_2), their ionization, dissociation and charge-exchange
1523 reactions, and their photochemistry would be required. The calculations based on a

1524 model with these characteristics can be of use when calibrating the instruments for the
1525 currently developed space missions to explore Jupiter's icy satellites—the ESA's
1526 JUICE (Grasset et al. 2013) and NASA's Mission to Europa (Pappalardo et al. 2015).

1527 **3.4. Possible future laboratory experiments to constrain the models**

1528 There are two groups of experiments and experimenters who deal with plasma
1529 interactions with water ice surfaces relevant to the icy moons: those who study
1530 irradiation processes in the ice (e.g., Loeffler et al. 2006; Strazzulla et al. 2007; Shi et
1531 al. 2011; Hand and Carlson 2011) and those who examine particle release from the ice
1532 (e.g., (Famá et al. 2008; Galli et al. 2016; Muntean et al. 2016)). In this chapter we
1533 will concentrate on the second group of experiments since the surface-release
1534 products are the source-components of Europa's atmosphere. So far, most
1535 experiments to quantify release processes were performed with water ice films on a
1536 microbalance to achieve a high measurement accuracy. However, these types of ice
1537 samples cannot be used for the study of the alteration processes inside the ice (e.g.,
1538 weathering) as the required dimensions and physical (porosity and density) and
1539 chemical properties are quite far away from the realistic ones in ice regolith surfaces.

1540 For Europa, the dominant process to release particles from the surface to the
1541 atmosphere is sputtering, whereas for Ganymede and Callisto sublimation may play
1542 an important role, too (Shematovich et al. 2005; Plainaki et al. 2015; Vorburger et al.
1543 2015). Sublimation of ices as a function of temperature can easily be measured in a
1544 vacuum chamber. Two recent meta-studies on sublimation pressures of ices, were
1545 presented by Andreas (2007) and Fray and Schmitt (2009).

1546 To accurately describe the sputtering process on Europa's icy surface, the
1547 quantity, the elemental composition, and the velocity distribution of all ejecta should
1548 be measured and determined as a function of the impactor's species (e^- , H^+ , O^+ , and S^+
1549 being the dominant species (Paranicas et al. 2002)) and energy (eV to MeV), the ice
1550 temperature and the surface's physical properties. The effect of ion irradiation of
1551 water ice is described by the physical quantity of the sputtering yield, i.e., the number
1552 of molecules ejected from the ice per incident ion. A commonly used experimental
1553 technique to assess sputtering yields consists of vapour depositing a thin film (100 –
1554 1000 nm) of compact (density $\approx 0.9 \text{ g cm}^{-3}$) amorphous ice onto a quartz
1555 microbalance (Famá et al. 2008; Shi et al. 2012). The ice film is then gradually
1556 sputtered and the observed frequency change of the quartz crystal allows to deduce

1557 the sputtering yield. For these thin ice films, surface charging effects usually do not
1558 bias sputtering yields as the surface potential is too weak to deflect the impinging
1559 energetic ions.

1560 Galli et al. (2016) experimented with a different approach to study sputtering
1561 properties of water ice. They created thick and porous ice samples of micrometer-
1562 sized water ice grains covered by a frost layer, which is much more representative for
1563 the regolith surface of icy moons. Since a thick and porous ice layer cannot be
1564 attached to a microbalance they had to resort to a different method of measuring the
1565 sputtering yield: the measurement of the pressure rise in the vacuum chamber caused
1566 by sputtering. Moreover, the thick and cold ice samples are excellent insulators
1567 (electric conductivity $\sim 10^{-15}$ S m⁻¹ even with NaCl impurities), resulting in a strong
1568 and long-enduring electrical charging of the ice during ion bombardment.

1569 The description of most sputtering experiments with ices before 2010 and of
1570 their outputs is included in an online database by the University of Virginia¹. The
1571 impacting species include H, noble gases up to Xe, C, N, O, and F, and noble gases up
1572 to Xe, with energies ranging from roughly 1 keV to 25 MeV. There is also reference
1573 to one study (Heide, 1984) about 100 keV electrons sputtering water ice molecules.
1574 Noble gas ions are often used as impactors for practical rather than for scientific
1575 reasons. Noble gases are easy to acquire and they do not react with surfaces and
1576 valves inside vacuum chambers contrary, for example, to sulphur. Argon is sometimes
1577 used in sputtering experiments as a proxy for sulphur because it has similar mass.
1578 Additional experimental studies not listed by Johnson and Liu (2010) were done by
1579 Farenzena et al. (2006) who shot 65 MeV Ba¹⁵⁺ ions at various ice species and by Shi
1580 et al. (2012) who used Ar ions to study electrical properties of irradiated water ice.
1581 Recent sputtering experiments with water ice on microbalances are presented by
1582 Muntean et al. (2016) (singly and doubly charged ions of solar wind energy) and by
1583 Galli et al. (2017) (Ar⁺, Ar²⁺, O⁺, O²⁺, O₂⁺, and electrons).

1584 For ion energies below 1 keV, the sputtering yield of ions in water ice can be
1585 described by a cascade of elastic collisions, whereas at higher energies, the so-called
1586 electronic sputtering dominates. Famá et al. (2008) derived a semi-empirical formula
1587 for the sputtering yield for the sum of both contributions, based on laboratory
1588 experiments with water ice films:

¹ http://www.people.virginia.edu/~rej/sputter_surface.html

1589
$$Y(E, m_1, Z_1, \theta, T) = \frac{1}{U_0} \left(\frac{3}{4\pi^2 C_0} \alpha S_n + \eta S_e^2 \right) \left(1 + \frac{Y_1}{Y_0} \exp\left(\frac{-E_a}{kT}\right) \right) \cos^{-f}(\theta) \text{ Eq. (2)}$$

1590 Equation (2) quantifies the sputtering yield as a sum of elastic and electronic
 1591 sputtering, described by the nuclear stopping power S_n and the electronic stopping
 1592 power S_e . The sputtering yield depends on energy E , mass of impactor m_1 , atomic
 1593 number of impactor Z_1 , the incidence angle θ from the 90 surface normal, and
 1594 temperature T . For U_0 , the sublimation energy of water (0.45 eV) is assumed, $C_0 = 1.3$
 1595 \AA^2 , $E_a = 0.06$ eV, and $Y_1/Y_0 = 220$ are constants. The temperature-independent
 1596 fraction in Equation (2) is due to the direct ejection of H_2O molecules. The
 1597 temperature-dependent term with the activation energy E_a becomes dominant above T
 1598 $= 120$ K and is due to the release of H_2 and O_2 (Johnson et al. 2004; Famá et al. 2008;
 1599 Teolis et al. 2009). Water radicals inside the irradiated ice react to form mainly H_2 and
 1600 O_2 , which are then released by sputtering (O_2) or diffusion (H_2). Given the angular
 1601 dependence of the yield in Equation (2), one expects an order of magnitude higher
 1602 sputtering yields at ion incidence angles between 60° and 80° than for perpendicular
 1603 ion impacts. The condition is that the ice sample is microscopically smooth. Küstner
 1604 et al. (1998) studied graphite surfaces of varying roughness on a μm scale and found
 1605 that the sputtering yield increased only by a factor of 2.5 when the ion incidence angle
 1606 increased from 0° to 80° . For a smooth graphite surface, they confirmed that the yield
 1607 increases by more than a decade.

1608 Cassidy et al. (2013) examined the data compiled by Johnson and Liu (2010)
 1609 and found that the semi-empirical sputtering Equation (2) fits data well for energies
 1610 below 100 keV. At higher energies, the formula by Johnson et al. (2009) for
 1611 electronic sputtering is more accurate. In Figure 24, we juxtapose the total sputtering
 1612 yield caused by O^+ ions (predicted with the formulae given by Famá et al. (2008) and
 1613 by Johnson et al. (2009) for energies below and above 100 keV, respectively) to the
 1614 yield of O_2 alone according to Teolis et al. (2010). The O_2 yield is more important for
 1615 atmospheric modeling than the total yield, as the latter is dominated by H_2O
 1616 molecules that will stick to the surface again. Figure 24 illustrates that the O_2 yield is
 1617 not a fixed fraction of the total sputtering yield, the ratio is highest for ion energies
 1618 around 10 keV.

1619 Impacting electrons are not expected to directly eject water molecules out of
 1620 the ice, nevertheless, they contribute to the production of O_2 , H_2 , and H_2O_2 (Hand and

1621 Carlson, 2011). In their review paper, Teolis et al. (2016) presented O₂ sputtering
1622 yields and penetration depths as a function of electron energy based on theory and
1623 experiments at low energies (Orlando and Sieger 2003). The first experiments at
1624 electron energies above 100 eV indicated that the yield does increase until 1 keV but
1625 the expected decrease above 1 keV cannot be reproduced yet (Galli et al. 2017).

1626 For atmospheric models, the energy distribution of the sputtered ejecta is as
1627 important as the sputtering yield. The characteristic energy of sputtered particles is
1628 orders of magnitudes lower than the energy of the impactors. Cassidy and Johnson
1629 (2005) modeled the sputter product energy distribution from any regolith target as the
1630 sum of the "planar binding" sputter product energy distribution (Boring et al. 1984)
1631 and a Maxwell energy distribution for the part of volatiles (O₂ and H₂) that interact
1632 and thermalize with neighbouring regolith grains before escaping:

1633

1634
$$f(E) = Y_1 \frac{2UE}{(E+U)^3} + Y_2 \frac{E}{(kT)^2} \exp\left(\frac{-E}{kT}\right) \text{ Eq. (3)}$$

1635

1636 The predicted energy of the thermalized O₂ and H₂ reaches only $kT = 0.008$ eV at
1637 regolith temperatures of 90 K. On the other hand, the median energy of ejected water
1638 molecules for 6 keV ions sputtering water ice was observed by Haring et al. (1984) to
1639 range between 0.15 and 0.19 eV. This implies that U in the first term of Equation (3)
1640 approximates the sublimation energy. The surface binding energy of water would be a
1641 decade smaller ($U = 0.054$ eV). Interestingly enough, a similar energy (0.05 eV) was
1642 found in experiments by Haring et al. (1984) for the bulk of O₂ released from water
1643 ice.

1644 From measurements of the angular distribution of sputtered H₂O from
1645 amorphous water ice films, Vidal et al. (2005) concluded that the angular distribution
1646 of water molecules follows $\sim \cos^{1.3} \phi$ at an ice temperature of 100 K. In this case, 2/3
1647 of the sputtered molecules leave the ice in a cone of $\phi = 40^\circ$ around the surface
1648 normal. In the most extreme case of H₂O ejected uniformly to all angles, ϕ would
1649 increase from 40° to 60° .

1650 The ion sputtering yield from laboratory measurements agrees between
1651 different groups within a factor of two (Johnson et al. 2004; Famá et al. 2008) for
1652 similar experiment set-ups, that is, for a thin film of pure water ice with densities $>$
1653 0.9 g cm^{-3} (Famá et al. 2008) and low temperatures ($T < 100$ K). This uncertainty per

1654 se would not be troublesome for atmosphere models of Europa, as other parameters
1655 are not more accurately known, either. Among other reasons, different studies take
1656 porosity into account by enhancing laboratory yields by a factor of 1–4 (Marconi,
1657 2007). Unfortunately, it is unclear if the subsequent release of radiolysed H₂ and O₂ is
1658 included in all publications the same way (see Teolis et al. (2016) for a recent
1659 overview).

1660 Galli et al. (2016) tackled the questions related to porosity by creating a 0.9
1661 cm thick and porous sample of water ice grains. Their first results indicate sputtering
1662 yields similar to previous lab experiments performed with water ice films sputtered
1663 off a microbalance. These results are thus consistent with the notion that sputtering
1664 from porous regolith ice is similar to dense monolayers of water ice. But more
1665 experiments at various energies, incidence angles, and different ion species are
1666 required to make a stronger statement. An inherent problem of experimenting with
1667 thick porous layer is the accuracy of the measurement methods (see Galli et al. 2017
1668 for a quantitative assessment).

1669 The sticking probability (or duration) is linked to the uncertainty introduced
1670 by porosity. Generally the H₂O is assumed to stick to the ice again, whereas O₂ and H₂
1671 do not permanently stick. This is justified, as experiments by Gibson et al. (2011)
1672 showed that for 0.3 and 0.7 eV energies, 98% to 99% of ejected water molecules stick
1673 to crystalline water ice. Because of that sticking probability, a sputtered water
1674 molecule is less probable to escape from within a porous ice layer. In contrast, the
1675 amount of O₂ and H₂ ejected is controlled only by the details of the radiation
1676 chemistry. Cassidy and Johnson (2005) therefore concluded from a Monte Carlo
1677 model that the reduction of the H₂O sputtering yield from water ice due to porosity is
1678 on the order of 70% compared to the sputtering from a dense and smooth ice surface.

1679 However, Cassidy et al. (2013) assumed that in reality the reduction due to
1680 porosity is compensated by the sputtering yield increase due to the irregular surface.
1681 Contrary to a smooth surface, ions will hit the grains in a rough surface at a wide
1682 distribution of impact angles, thus the average sputtering yield for a perpendicular
1683 incidence angle will be closer to the yield observed at a 45° incidence angle. This
1684 effect of porosity on angular dependence is only expected for the regime of single
1685 elastic collisions up to few keV energies of impacting ions.

1686 If experimental results from coarse graphite surfaces (Küstner et al. 1998) also
1687 apply to water ice, the yield from porous ice varies only by a factor of 2 or 3 for the
1688 full range of incidence angles in contrast to the order of magnitude expected from
1689 $\sim \cos^{-f}(\theta)$ (Equation (2)). To decide whether this affects atmospheric models one has
1690 to integrate the sputter yield over the whole angular range of the ion distribution. A
1691 spatially uniform ion distribution would result in a two times lower sputtering
1692 production if we adopt the flat angular dependence instead of the cosine-law of
1693 Equation (2). But more experimental results, in particular for water ice, are needed
1694 (see Section 4) before discussing potential effects on atmospheric models.

1695 Another element of uncertainty is the charge state of the ions. In their
1696 alternative interpretation of Europa's atmosphere, Shemansky et al. (2014) proposed
1697 that sputtering was dominated by multiply charged O and S ions with charge state of 3
1698 and higher. Aumayr and Winter (2004) showed that for perfect insulator surfaces such
1699 as NaCl and LiF the sputtering yield increases with recombination energy and thus
1700 with the charge state of the impacting ion (see also reviews of this topic in Kallio et
1701 al. 2008 and Wurz et al. 2010). Aumayr and Winter (2004) did not study ice targets.
1702 Cooper and Tombrello (1984) found that the sputtering yield from a water ice film
1703 doubled when they switched from F^{4+} to F^{8+} in the MeV range, but these charge states
1704 and energies are not representative for Europa's plasma environment. In more recent
1705 experiments, Muntean et al. (2016) and Galli et al. (2017) found no significant
1706 difference in sputtering yields between singly and doubly charged C, N, O, and Ar for
1707 energies between 1 and 50 keV

1708 Other areas where little or no experimental results exist include the release
1709 yield due to high energy electrons and due to impacting molecules (Equation (2)
1710 applies only to single atoms). The case of impacting O_2 or O_2^+ is of particular interest
1711 for Europa (Dols et al. 2016): Galli et al. 2017 found that the sputtering yield due to
1712 O_2^+ in the electronic sputtering regime is two times higher than expected, but no
1713 general framework exists yet to accommodate these data. The sputtering yield due to
1714 electrons may be orders of magnitude smaller than for ions of the same energy (Galli
1715 et al. 2017). Nevertheless, electron irradiation would still play an important role for
1716 Europa's surface: due to their much deeper penetration depth, energetic electrons
1717 from the Jovian magnetosphere can irradiate the top centimeters of ice layers, whereas
1718 ions of that energy are stopped within the top 10-100 μm (Hand and Carlson 2011).

1719 Since the open issues discussed above cannot be quantified with first-principle
1720 analyses or numerical methods only (Johnson, 1989; Cassidy and Johnson, 2005), the
1721 role of laboratory work becomes substantial for providing information in the
1722 following directions:

1723 *1. Identify the ways in which porosity affects sputtering*

1724 Porosity, ion incidence angle, and surface roughness should be varied independently
1725 from each other in laboratory tests similar to the ones described in Galli et al. (2016)
1726 to see if sputtering yield, energy distribution, and angular distribution are similar for
1727 deep porous ice and ice films.

1728 *2. Study radiolysis products from porous water ice and understand for how long do*
1729 *H₂ and O₂ remain trapped inside such types of ice*

1730 If the atmospheric O₂ is the direct release product, looking at the O₂ atmosphere we
1731 are mostly sensitive to the dayside surface close to the equator and, in particular, to
1732 the subsolar point (Plainaki et al. 2013).

1733 *3. Determine how the chemical composition of the sputtered ejecta relates to that of*
1734 *the surface; determine the timescale for space-weathering*

1735 Sputtering does not give a 1:1 stoichiometric representation of the surface
1736 composition as we know from sputtering experiments with Moon and Mercury
1737 analogues (Dukes et al. 2011) that volatiles (e.g. Na) are preferentially released from
1738 irradiated silicates. As a result, the surface composition will change with respect to
1739 the bulk composition (the so-called “space weathering”) until it reaches a new steady
1740 state. As a result, the elements less efficiently sputtered will be enhanced in a thin
1741 surface layer compared to the bulk composition, whereas the composition of the
1742 ejecta will reflect the bulk composition. Is the timescale to reach this steady state
1743 similar to the very short timescales (typically ~years for the uppermost μm) derived
1744 for sputtering, radiolysis, and regolith growth (Cooper et al. 2001; Johnson et al.
1745 2004)?

1746 *4. Determine the O₂ release yield due to high-energy electrons*

1747 Very little is known about sputtering yield (direct or via radiolysis) from electron
1748 precipitation (Heide, 1984; Orlando and Sieger, 2003). The recent review paper by
1749 Teolis et al. (2016) makes predictions for the O₂ yield from electrons irradiating water
1750 ice including energies > 100 eV, which have never been studied in laboratory. This
1751 gap should be filled.

1752 5. *Study scattered particles, and in particular O^+ and S^+ ions reflected from the*
1753 *surface; study the sputtering yield from multiply charged ions*

1754 These magnetospheric ions can be back-scattered as ions, neutrals (Wieser et al.
1755 2016), or possibly negative ions.

1756 6. *Expand the description of the sputtering yield to molecular species.*

1757 It is of interest to understand the effects of molecules impacting water ice.

1758 **4. Definition of suitable observation strategies for future**

1759 **missions to Europa**

1760 Europa's tenuous atmosphere represents the actual interface between the icy surface of
1761 this moon and the giant planet's environment. In this perspective, its characterization
1762 is of key importance to achieve a fully understanding of the alteration processes
1763 induced on the icy surfaces by the radiation environment. A few examples illustrating
1764 this point are:

- 1765 • The deposition of neutral species from the tenuous atmosphere onto the moon's
1766 surface will spectrally mask the weathering products (deposition of H_2O) or
1767 directly start new chemical patterns (e.g.: oxidation by oxygen-bearing species)
- 1768 • The efficiency of weathering and particle release from the surface may be
1769 reduced by the ionosphere.

1770 It is, therefore, clear that a full interpretation of surface data and an in depth
1771 understanding of the surface evolution history, has as a necessary prerequisite the
1772 accurate determination of the role of the tenuous atmosphere in the interactions
1773 between the icy moons and the Jupiter's magnetospheric environment. Moreover to
1774 understand the mass and energy exchange between Europa and Jupiter's
1775 magnetosphere, the detailed characterization of the tenuous atmosphere as a boundary
1776 region between the moon and the giant planet's magnetosphere, is fundamental. Many
1777 factors determining the characteristics of the tenuous atmosphere are not obviously
1778 assessed a priori (e.g. the actual flux of charged particles impacting the surface; the
1779 density of the ionosphere). Therefore, the understanding of the generation and
1780 dissipation mechanisms of Europa's tenuous atmosphere requires a long term
1781 monitoring of several parameters, with comparable coverage and sampling in time
1782 and space. The achievement of the related science objectives of future missions to

1783 Europa will be feasible only through an interdisciplinary approach characterized by
1784 coordinated observation scenarios and joint campaigns in payload operations.
1785 Namely, it is of key importance to measure - in the larger possible extent allowed by
1786 the details of the flybys phase - the following quantities:

- 1787 • Density of neutral species
- 1788 • Density of ionosphere and charged particles fluxes
- 1789 • Efficiency of interactions of the tenuous atmosphere with particle and photon
1790 radiation fields

1791 While the JUICE payload elements have the potential to assess these phenomena, it
1792 should be stressed that each dataset alone can not fully assess the moon's atmosphere
1793 behavior; the highly dynamical nature of the involved processes requires a joint
1794 analysis to properly interpret the data correlation in a vast extent. Through the
1795 planning of potential synergies between different datasets to be obtained during the
1796 two Europa flybys, a contribution to the achievement of the JUICE scientific
1797 objectives related to Europa will be provided (see Table 5). In particular, the
1798 measurements related to the moon's tenuous atmosphere will help to answer the
1799 following JUICE science objectives:

- 1800 • Determine the composition of the non-ice material at Europa, especially as
1801 related to habitability;
- 1802 • Search for liquid water under the most active sites at Europa;
- 1803 • Study the recently active processes at Europa;
- 1804 • Understand the moons as sources and sinks of Jupiter's magnetospheric
1805 plasma;

1806 It is clear that such considerations, intimately of interdisciplinary nature, are of
1807 significant importance while planning the JUICE mission observations since the latter
1808 can dramatically increase our knowledge on the involved physical phenomena. In this
1809 concept, the following inter-disciplinary science goals can be defined:

- 1810 • Characterization of the atmospheric environment of Europa
- 1811 • Investigation of the interactions between the tenuous atmosphere of Europa
1812 and the Jovian magnetosphere, with respect to the relation between the time-
1813 scales of their variations
- 1814 • Study of the moon atmosphere - surface coupling as a main agent for both the
1815 atmosphere generation and the surface weathering

1816 Each one of the proposed goals can be further structured in one or more specific
1817 interdisciplinary science objectives (see Table 5) with respect to their compatibility to
1818 the mission resources and instrument requirements. In Table 5 we also demonstrate
1819 that each one of the proposal's science objectives is directly related to one or more
1820 JUICE mission Science Objectives. It is furthermore emphasized that in order to
1821 accurately plan such synergies, the use of a global model for the tenuous atmosphere
1822 of Europa (see Section 3.3) is strongly required.

1823 Below we provide an example of possible interdisciplinary research related to
1824 the Europa's tenuous atmosphere to be done once the JUICE s/c has arrived at the
1825 moon. Given the variability of the environment around the icy moon, such studies can
1826 be considered to refer to the more general thematic of planetary space weather
1827 (Lilensten et al. 2014; Plainaki et al. 2016). In Figure 25, a snapshot corresponding to
1828 the JUICE s/c arrival to Europa is shown. The JUICE s/c will be at a distance of \sim
1829 22,745 km from Europa with a phase angle of $\sim 87.4^\circ$. On the same figure, the
1830 expected spatial distribution of the O₂ tenuous atmosphere, for this exact
1831 configuration between Jupiter, Europa and the Sun, as derived from the EGEON
1832 model (Plainaki et al. 2012; 2013), is overlaid. During approach, JUICE will cover the
1833 regions above the trailing terminator. This configuration favors also the direct search
1834 for the occurrence of possible plumes (Huybrighs et al. 2017) also in the northern
1835 hemisphere as well as the detection of plume-material (possibly scattered from
1836 condensates) originating from the southern hemisphere, with UVS, SWI, JANUS,
1837 MAJIS and PEP-JNA (the latter at distances smaller than $\sim 12,000$ km) (science
1838 objective G1.2 in Table 1). Detailed studies of the chemical composition of Europa's
1839 exosphere will be performed with PEP-NIM (Wurz et al. 2014). This configuration
1840 allows also the detection in the dayside of non-LTE emissions from minor
1841 components (CO₂, CO, Na, H₂O) and airglow emissions as well; at the nightside the
1842 detection of airglow emissions from water and O₂ products (O, OH, H) can be
1843 attempted since the existence of long-lived species in excited states cannot be ruled
1844 out in the almost collisionless environment of Europa. Moreover, this configuration is
1845 favorable for the determination of the tenuous atmosphere morphology above both the
1846 illuminated and non-illuminated hemispheres allowing the identification of possible
1847 inhomogeneity (science objective G1.2) and, consequently, a direct comparison with
1848 the spatial distributions provided by the existing atmosphere models. It is stressed that

1849 current models predict different spatial distributions for the O₂ tenuous atmosphere of
1850 Europa. The EGEON model assumes a strong dependence of the release yields on
1851 surface temperature, resulting in the O₂ density asymmetry seen in Figure 25.
1852 Conversely, other authors consider this dependence negligible, implying a more
1853 symmetric tenuous atmosphere (Cassidy et al. 2013). Therefore, the observation
1854 geometry in Figure 25 allows one to evaluate the role of surface temperature in the
1855 generation of the O₂ tenuous atmosphere. Instruments such as SWI and PEP-JNA can
1856 map before the flyby the densities above subsolar and antisolar points, allowing a
1857 clean discrimination between the two scenarios.

1858

1859 **5. Conclusions**

1860 Europa's tenuous atmosphere is a complex field of active ongoing research. Although
1861 the existing observations of Europa's exosphere have provided important constraints
1862 for determining its generation and loss rates, a direct measurement of the main
1863 exospheric species (i.e. H₂O, O₂, H₂) has not been performed yet and the limited
1864 available observations are just proxies of these bulk constituents. In the absence of an
1865 adequate number of in situ observations, modeling becomes a fundamental tool for
1866 understanding the nature of Europa's neutral environment and for planning future
1867 space observations.

1868 Sputtering and radiolysis are key source processes for the atmosphere of
1869 Europa provoking also the alteration of the moon surface, in terms of composition,
1870 reflectance, volatility and porosity. Understanding the structure and the emission
1871 properties of Europa's rarefied atmosphere allows to infer about the relative
1872 composition of the parent molecules released from the moon's icy surface due to its
1873 bombardment by Jupiter's magnetospheric plasma. At the same time, the correct
1874 interpretation of surface data requires necessarily the accurate determination of the
1875 tenuous atmosphere in the plasma-icy moon interactions. Being also the tenuous
1876 atmosphere the boundary region between Jupiter's magnetosphere and the icy surface,
1877 it becomes the laboratory for studying the mass and energy exchange between the
1878 moon and the giant planet. The science of the Europa environment, therefore,
1879 becomes a critical and interdisciplinary aspect of the study of the whole Jovian
1880 system.

1881 In the current paper, in a larger view approach that involves different
1882 disciplines, we reviewed the available in situ and telescope observations and
1883 compared a large part of the existing plasma and atmosphere models. We discussed
1884 different controversial issues among models and presented the advantages and
1885 disadvantages of different modeling techniques. Based on our review, we defined the
1886 required characteristics for a community-unified atmospheric model in means of main
1887 physical phenomena to be included, acceptable assumptions and approximations. We
1888 conclude that there is an urgent need to implement such a global model for the
1889 environment around Europa, paying special attention to its spatial and temporal
1890 variability. Such a project would be very important for planning correctly the
1891 observations that will address the main science goals during future missions to the
1892 Europa moon.

1893

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2269 **Figure Captions**

2270 **Figure 1:** An example of the Knudsen number profile in the O₂-dominant near-
 2271 surface atmosphere of Europa. Here, the O₂ density profile (Shematovich et al. 2005)
 2272 has been used. For the calculation of the O₂ mean free path the elastic collision cross
 2273 section with mean value of $3 \cdot 10^{-15} \text{ cm}^2$ have been taken. Vertical and horizontal
 2274 dashed lines indicate the formal definition of the exobase.

2275 **Figure 2:** First detection of Europa's oxygen atmosphere in an HST/GHRS spectrum
 2276 from 1994 (bottom) and two follow-up spectra from 1996 (Hall et al. 1998)

2277 **Figure 3:** (A) Excitation rates producing the OI 1304 Å and OI 1356 Å emissions
2278 from electron-impact on O and O₂. (B) Theoretical 1356-Å/1304-Å brightness ratio
2279 for pure O (solid) and pure O₂ (dashed) atmospheres based on the rates in (a). In
2280 addition, mixed O-O₂ atmosphere cases are shown that match the observed ratios
2281 (dotted, dashed-dotted). (C) Contour plot showing the relation of the measured
2282 brightness to electron density and atmospheric column density.

2283 **Figure 4:** Europa's UV spectrum composite of the 7 highest quality NH Pluto-Alice
2284 spectra. The OI 1356 Å line is ×2 brighter than OI 1304 Å, which is consistent with
2285 previous observations and an O₂ excitation source.

2286 **Figure 5:** Left: Cassini ISS NAC visible image with clear filters of Europa in eclipse
2287 (Cassidy et al. 2008, their Fig. 2b with enhanced contrast) shows a strong emission
2288 surplus in the sub-Jovian northern quadrant. Middle: A local emission surplus is
2289 similarly detected in a composite HST/ACS/SBC F125LP image of four exposures of
2290 Europa's OI 130.4 nm and OI 135.6 nm aurora in eclipse. Right: HST/ACS/SBC
2291 PR130L observations of the OI 1356 Å aurora in eclipse (Sparks et al. 2010,
2292 reprocessed image). Europa's location is relatively uncertain in the ACS figures.

2293 **Figure 6:** Sketch of the systematic changes of the aurora morphology and the relation
2294 of Europa's position in the magnetosphere (after Roth et al. (2016)). Some images
2295 show a less clear and sometimes differing behavior, but a rough correlation is still
2296 seen in most of the images.

2297 **Figure 7:** Plasma environment between Io and Europa. From Bagenal et al. (2015).

2298 **Figure 8:** (a) Ion temperature (Plasma Science instrument) vs. electron density
2299 (Plasma Wave instrument) derived from Galileo measurements between 8.9 and 9.9
2300 R_J, excluding the region within 2.5 R_E of Europa. Color corresponds to measurement
2301 dates. The solid, dashed and dotted lines show the median, quartiles, 10th- and 90th-
2302 percentile values respectively. The double-headed arrows show the variation in
2303 density with latitude for high and low ion temperatures. The straight line is drawn by
2304 eye to give a simple power-law relation between temperature and density (top, right
2305 corner). Galileo's 1 Europa flyby is labeled by E12. Figure taken from Bagenal et al.
2306 2015. (b). Histograms of electron density, measured by Galileo PWS data, ion
2307 temperature and azimuthal velocity measured by Galileo PLS data. From Bagenal et
2308 al. 2015.

2309 **Figure 9:** Observed and modeled field for the Europa flyby E4 in the Cartesian
2310 Coordinate System. The measured field is shown by red. The background field is
2311 shown by thin black. The predicted field for the internal permanent dipole plus
2312 induction for external field is shown by green. Blue, black and cyan stand for the
2313 predicted field by using the Alfven wing model to describe the external local currents
2314 for internal sources: induction only, induction plus dipole and induction plus dipole
2315 plus quadrupole, respectively. Adapted from Schilling et al. 2004.

2316 **Figure 10:** Histogram of magnetic field values at Europa's average radial distance of
2317 $9.38 R_J$ for the VIP4 and Khurana magnetic field model. From Bagenal et al. 2015

2318 **Figure 11:** ENA image (energy range 50-80 keV/nuc) of the Jupiter environment
2319 obtained by CASSINI/INCA (Krimigis et al. 2002).

2320 **Figure 12:** Deconvolved 50-80 keV ENA image (counts in 15h) of the Jupiter
2321 environment obtained by CASSINI/INCA at 140 RJ (Mauk et al. 2003)

2322 **Figure 13: Upper panel.** ENA flux*(R/100)² versus Cassini distance to Jupiter for
2323 different energy ranges (Mitchell et al. 2004). **Lower panel.** ENA energy spectrum
2324 obtained by Cassini/INCA (Mitchell et al. 2004).

2325 **Figure 14: Upper panel (a).** Observed INCA hydrogen ENA image in the 55-90 keV
2326 range obtained by Cassini during its distant flyby of Jupiter. **Upper panel (b).** Best fit
2327 simulated ENA image assuming a H₂ neutral gas distribution displayed in the lower
2328 panel of this figure. **Lower panel (a).** Resulting neutral gas distribution required to
2329 obtain the best-fit simulated ENA image of the figure's upper panel. **Lower panel (b).**
2330 Same format as in the figure's upper panel, but without the instrumental PSF and
2331 geometrical factor applied to the image.

2332 **Figure 15:** Lines of equal electric potential (in V), which are also streamlines of
2333 electron flow. The plasma flows from the left. The electric field is decreased and
2334 modified in the close vicinity of Europa in a way that the electrons are slowed down
2335 and mostly swept around Europa (Saur et al. 1998).

2336 **Figure 16:** Observed and modeled magnetic field for the E4 flyby in the EPhiO
2337 coordinate system. Red line shows the measurements of *Kivelson et al.* (1997); dashed
2338 black line shows the modeled field with no induced field in the interior; Blue, green,
2339 and black line show the model results including induction in a 100-km-thick ocean
2340 located beneath a crust of 25 km for ocean conductivities of 100, 250, and 500 mS/m,
2341 respectively. From *Schilling et al.* (2007).

2342 **Figure 17:** Left. Alfvénic current in 10^{-7} A/m² in a cross section through the northern
2343 Alfvén wing for the E4 flyby conditions and without induction. Right. Same as left
2344 panel but with induction (Schilling et al. 2008).

2345 **Figure 18:** Plasma density distribution around Europa during the Galileo E4 flyby as
2346 modeled by Rubin et al. (2015). (a) O^+ mass density distribution in the equatorial
2347 plane in EphiO coordinates. The trailing hemisphere facing the inflow of the
2348 magnetospheric plasma is on the left hand side. The positive EphiO y-direction points
2349 towards Jupiter. The black line shows Galileo’s trajectory projected onto this plane. (b)
2350 O^+ mass density in the close vicinity of Europa in three perpendicular cuts. Panels (c)
2351 and (d) show the same for O_2^+ . Both species show an asymmetry about the upstream
2352 flow direction.

2353 **Figure 19:** Contours of densities and temperatures for ions in Europa’s equatorial
2354 plane. The densities of three species are shown on the left: O_2^+ , which is the primary
2355 pickup ion from Europa’s atmosphere, and sulphur and oxygen species from the
2356 jovian magnetosphere. The average temperature of these ions is shown on the right.

2357 **Figure 20:** Height distributions of the number density n (panel (a)), and average
2358 thermal energy T_m (panel (b)) of molecular (solid lines) and atomic (dashed lines)
2359 oxygen in model (Shematovich, 2006) of Europa’s atmosphere. The dashed–dotted
2360 line in panel (a) shows the distribution of the number density of molecular oxygen
2361 from model by Saur et al. (1998).

2362 **Figure 21:** H_2O density distribution around Europa according to the EGEON model.
2363 The release yields used in EGEON were updated according to the description
2364 provided in Milillo et al. (2016). Positive X-axis points to Europa’s orbital direction,
2365 Z-axis to the spin direction.

2366 **Figure 22:** O_2 density distribution around Europa at different orbital phases,
2367 according to the EGEON model.

2368 **Figure 23:** O_2 source rates from Europa atmosphere models. There is a long-standing
2369 debate over both the source rate and source process: colors indicate the charge-
2370 particle population responsible for producing most O_2 in each model. “Energetic”
2371 refers to non-thermal ions with energies of >10 s of keV, “thermal” refers to the Io
2372 plasma torus ($T \sim 100$ eV), “ O_2^+ pickup” refers to ionized O_2 from Europa’s
2373 atmosphere.

2374 **Figure 24:** Predictions of the total sputtering yield (Famá et al. 2008; Johnson et al.
2375 2009) (upper curves) versus the O₂ yield alone (Teolis et al. 2010) for oxygen ions
2376 irradiating water ice at 100 K.

2377 **Figure 25:** JUICE mission phase 2.b. Europa's trailing hemisphere as viewed from
2378 the JUICE s/c while approaching the moon at a distance of ~ 22,735 km, on 13 Feb
2379 2031 at 1h40m prior to the closest approach. In transparency, the O₂ tenuous
2380 atmosphere densities on the sagittal plane, for this exact configuration between
2381 Jupiter, Europa and the Sun, as derived from the EGEON model (Plainaki et al. 2013).
2382 The diffuse high-altitude component shows a clear asymmetry between the
2383 illuminated and non-illuminated hemispheres. Simulations performed using the
2384 CELESTIA open-source software with the SPICE kernels for JUICE and Solar
2385 System bodies.

2386

2387

2388 **Table Captions**

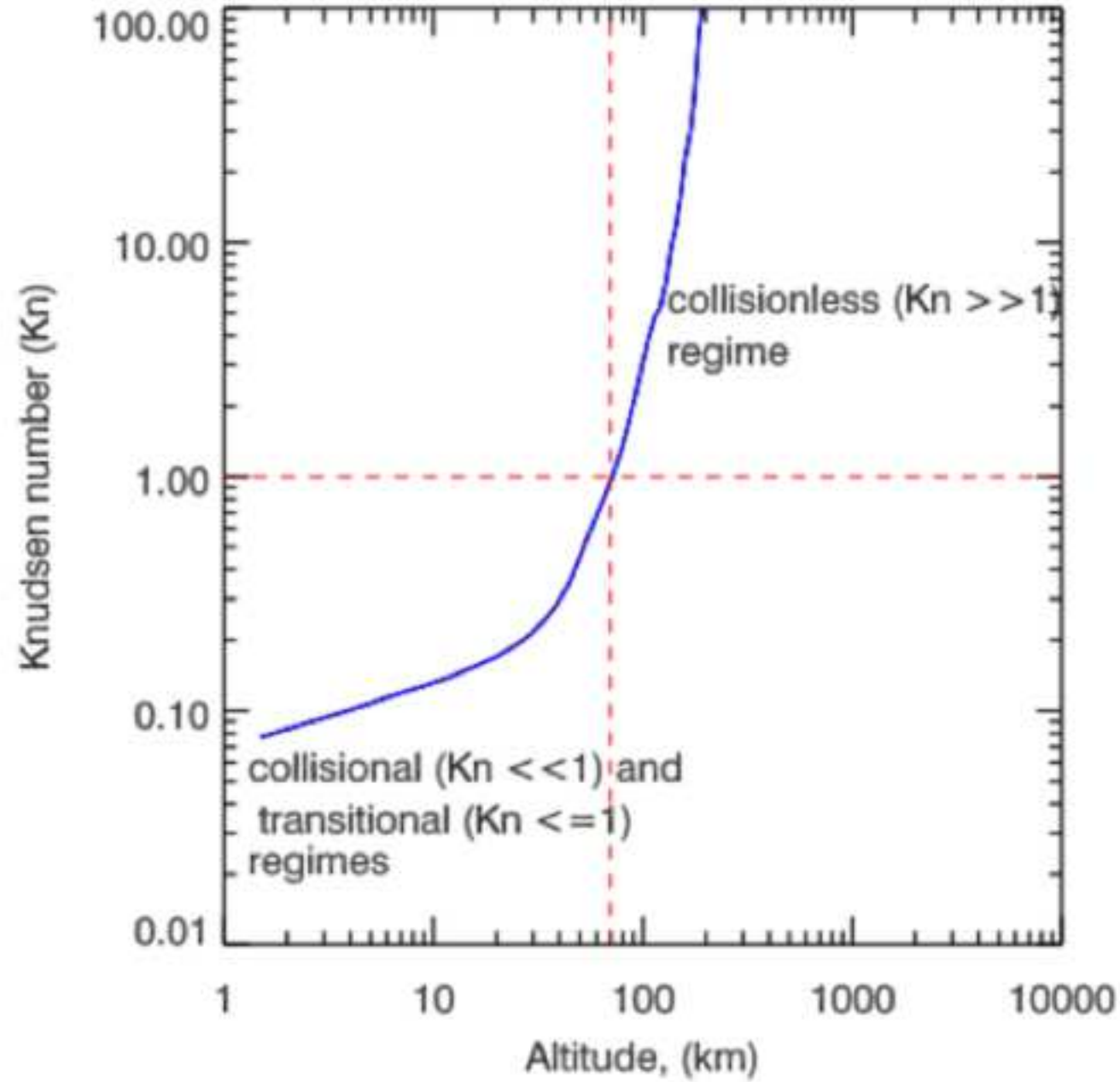
2389 **Table 1:** Overview of the observations of Europa's tenuous atmosphere

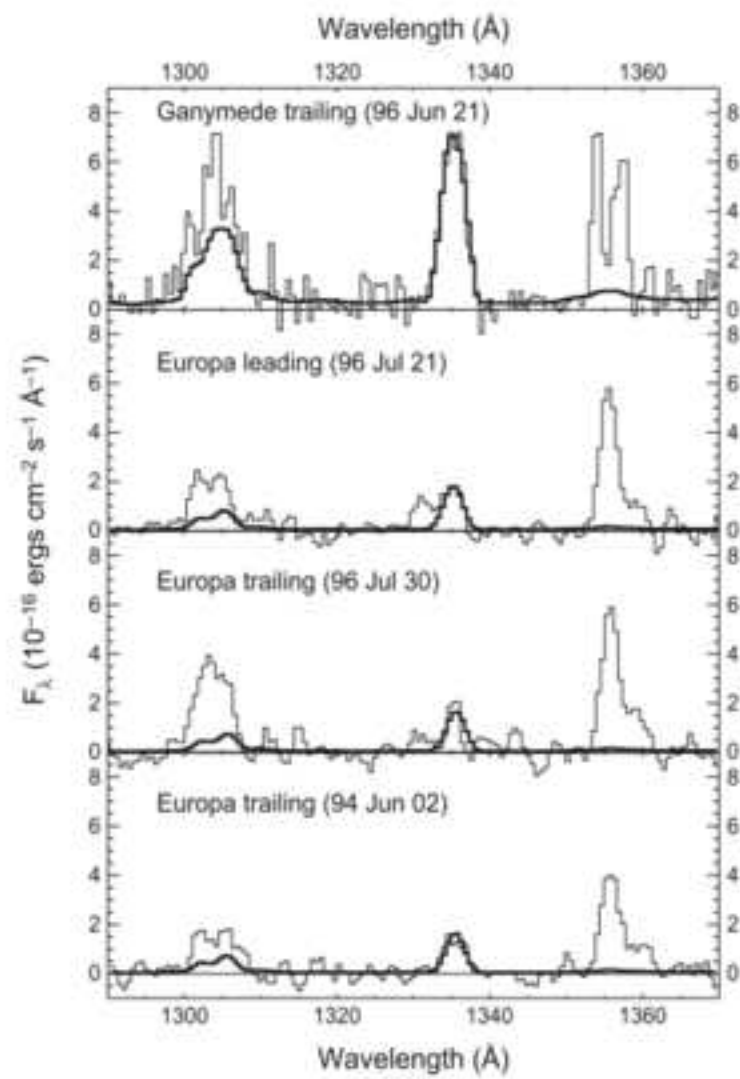
2390 **Table 2:** Comparison among the plasma model assumptions

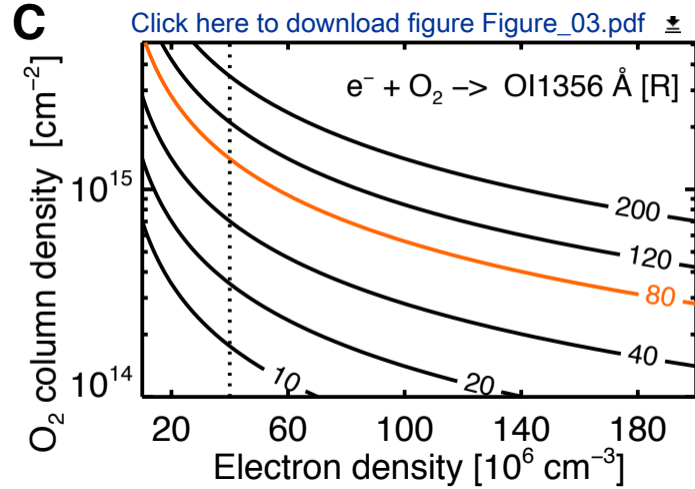
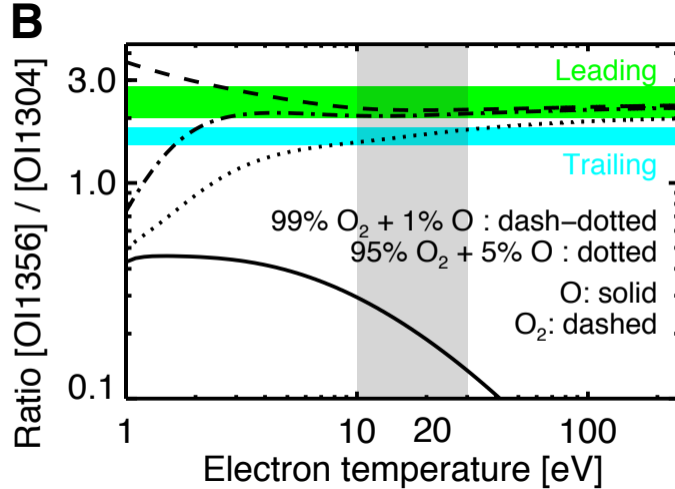
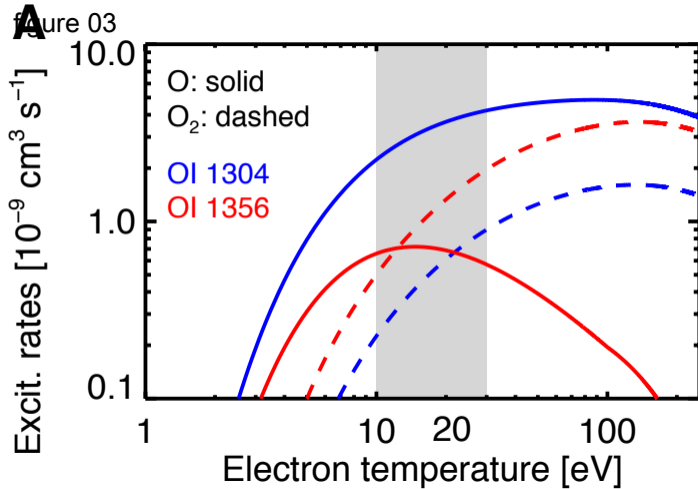
2391 **Table 3:** Comparison among the atmosphere model assumptions

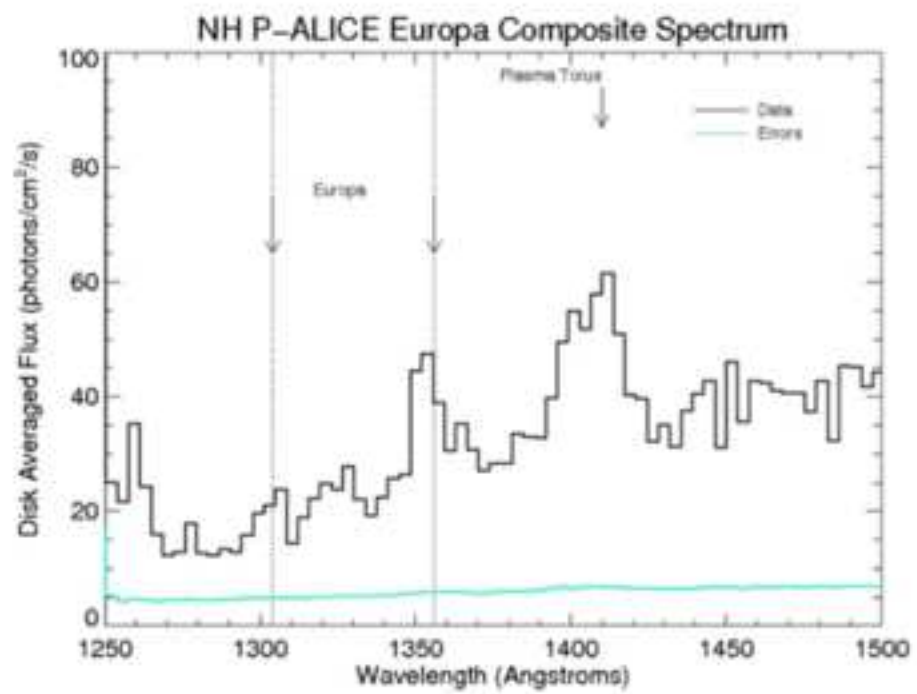
2392 **Table 4:** Comparison among the atmosphere model outputs

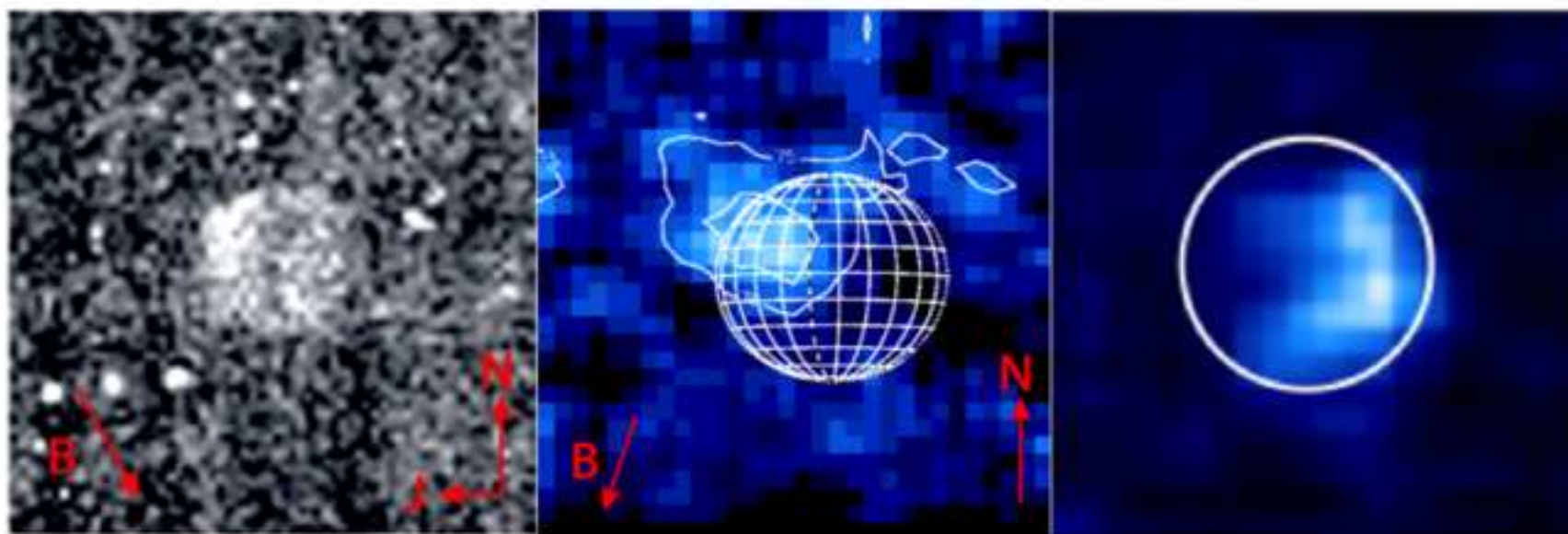
2393 **Table 5:** Interdisciplinary science goals, objectives and requirements related to the
2394 Europa atmospheric science



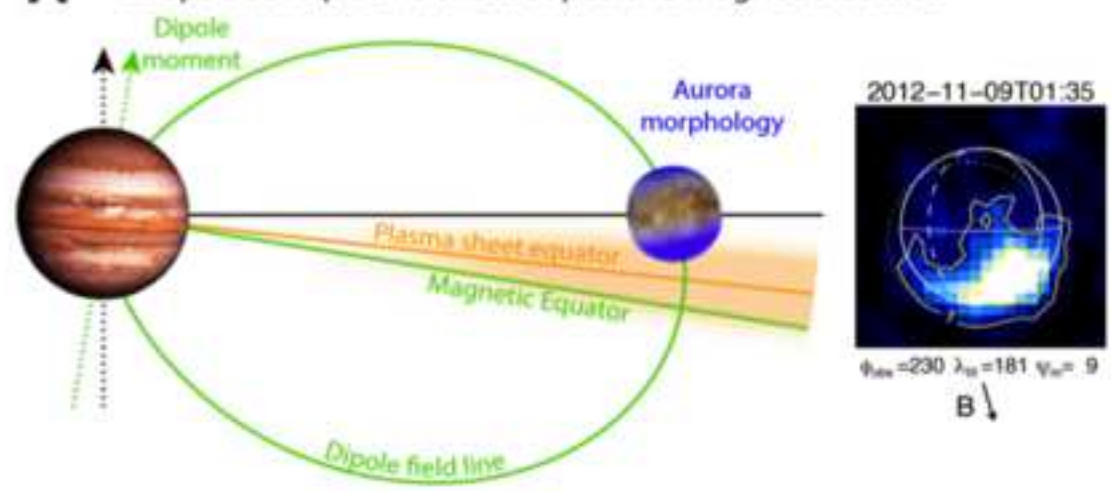




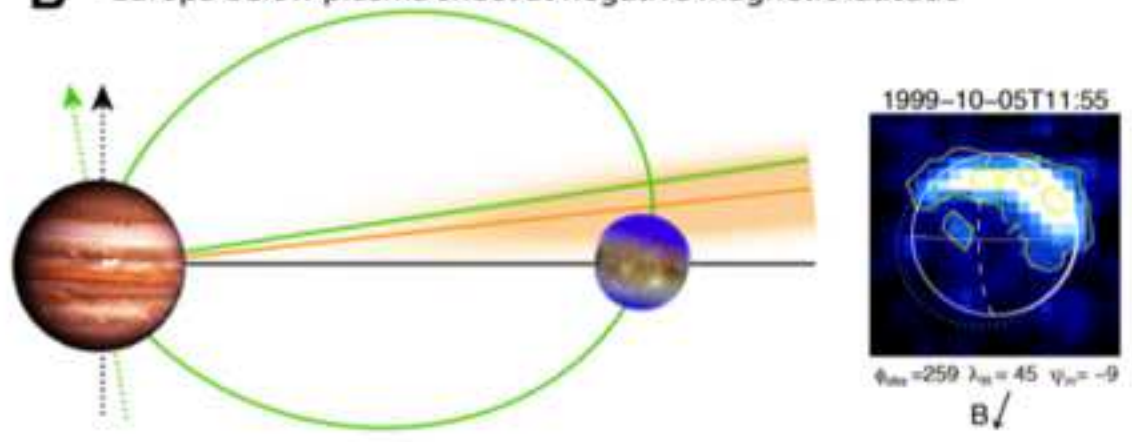


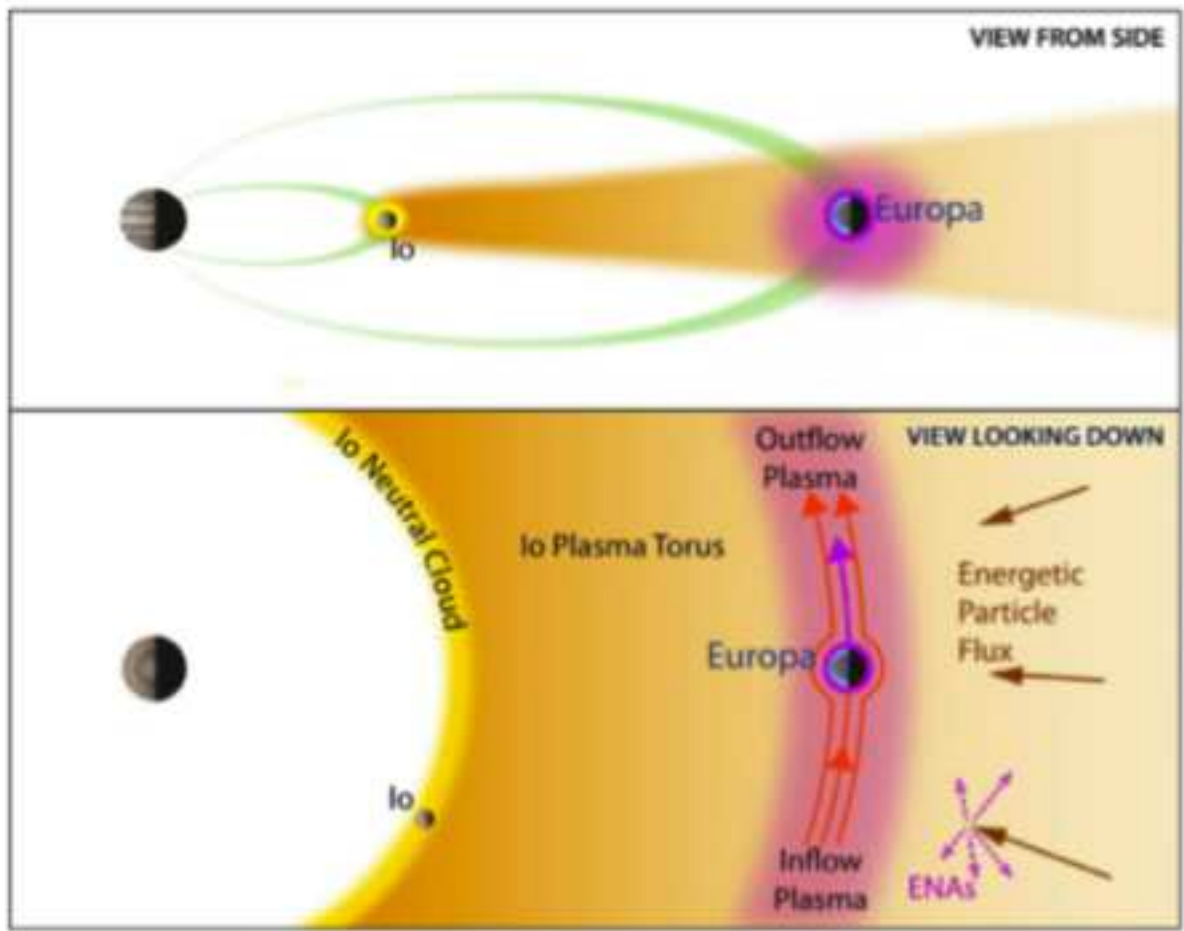


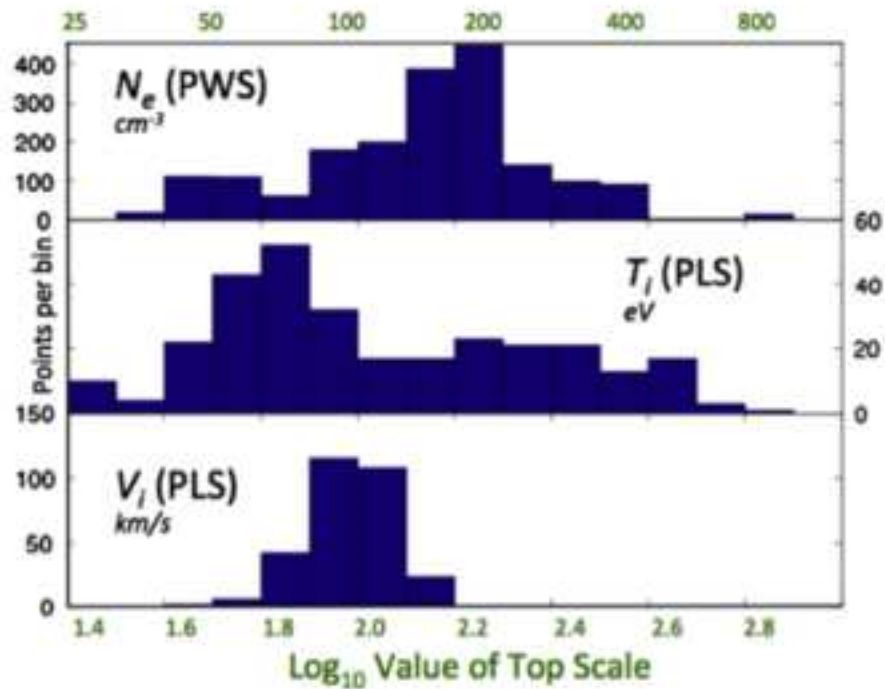
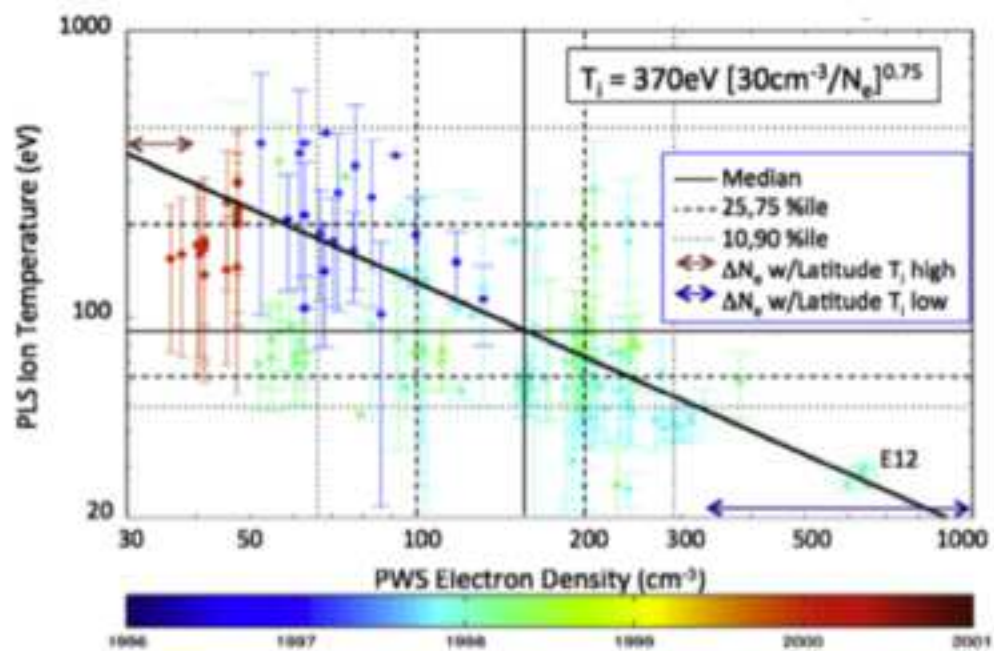
A - Europa above plasma sheet at positive magnetic latitude

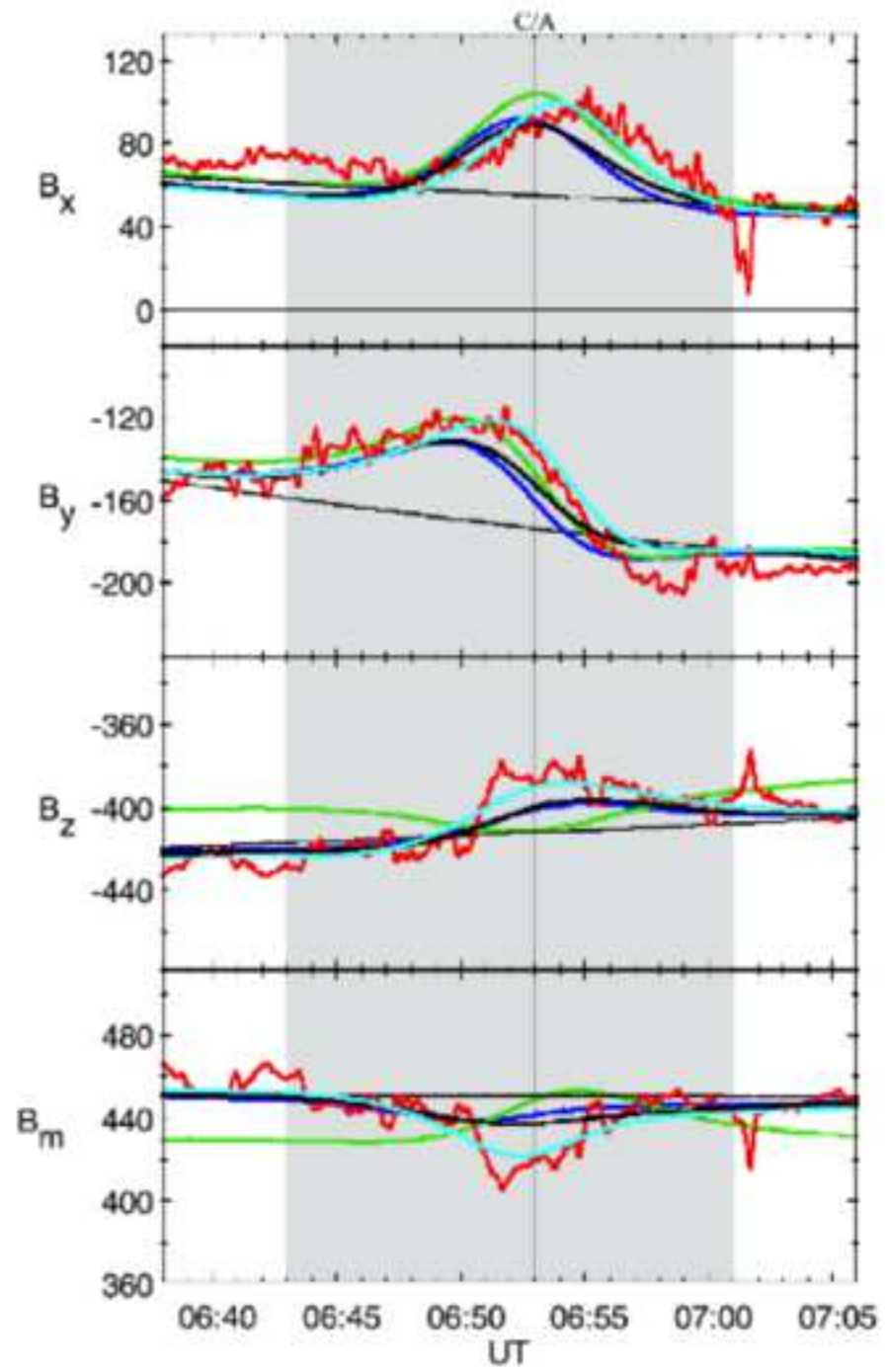


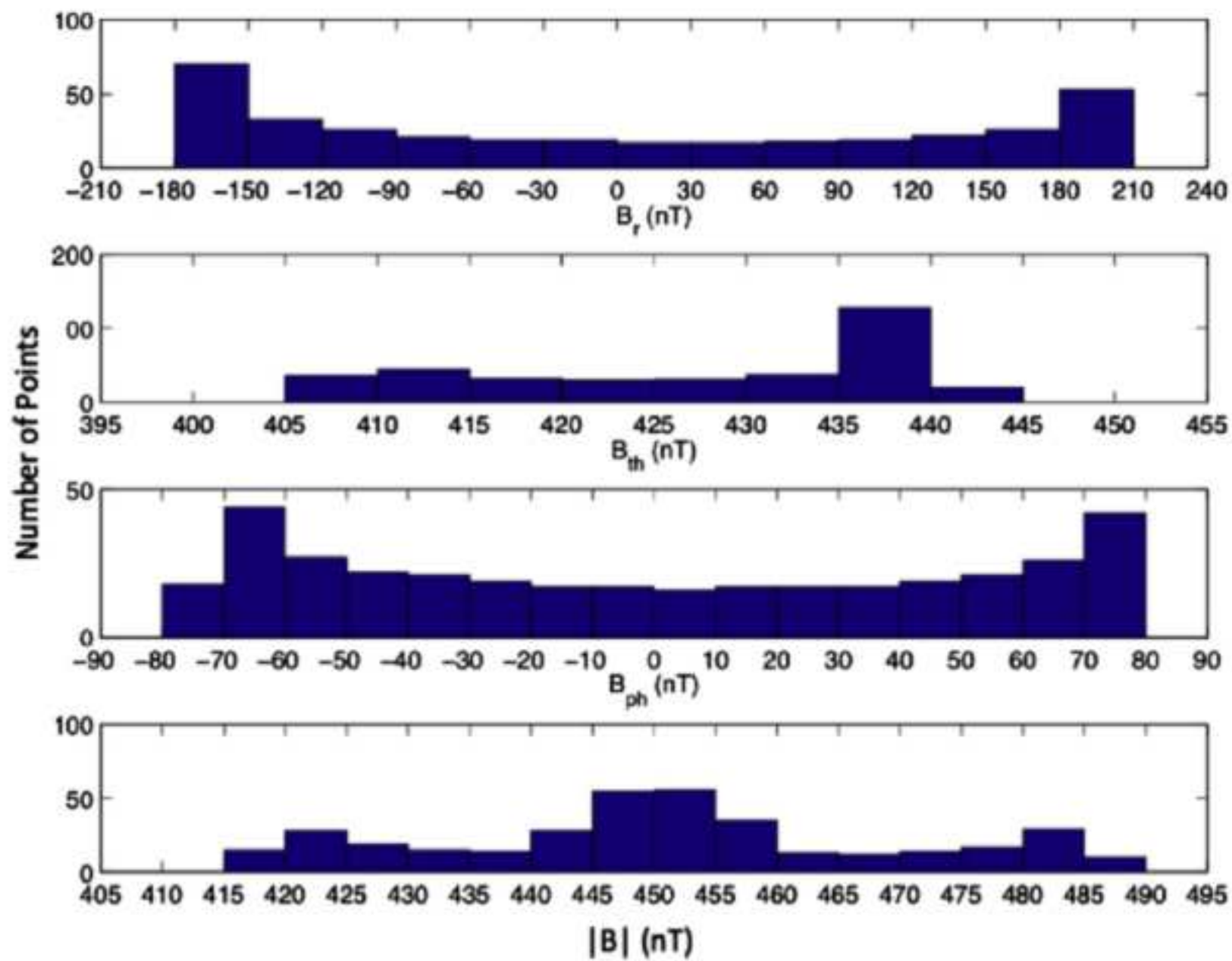
B - Europa below plasma sheet at negative magnetic latitude

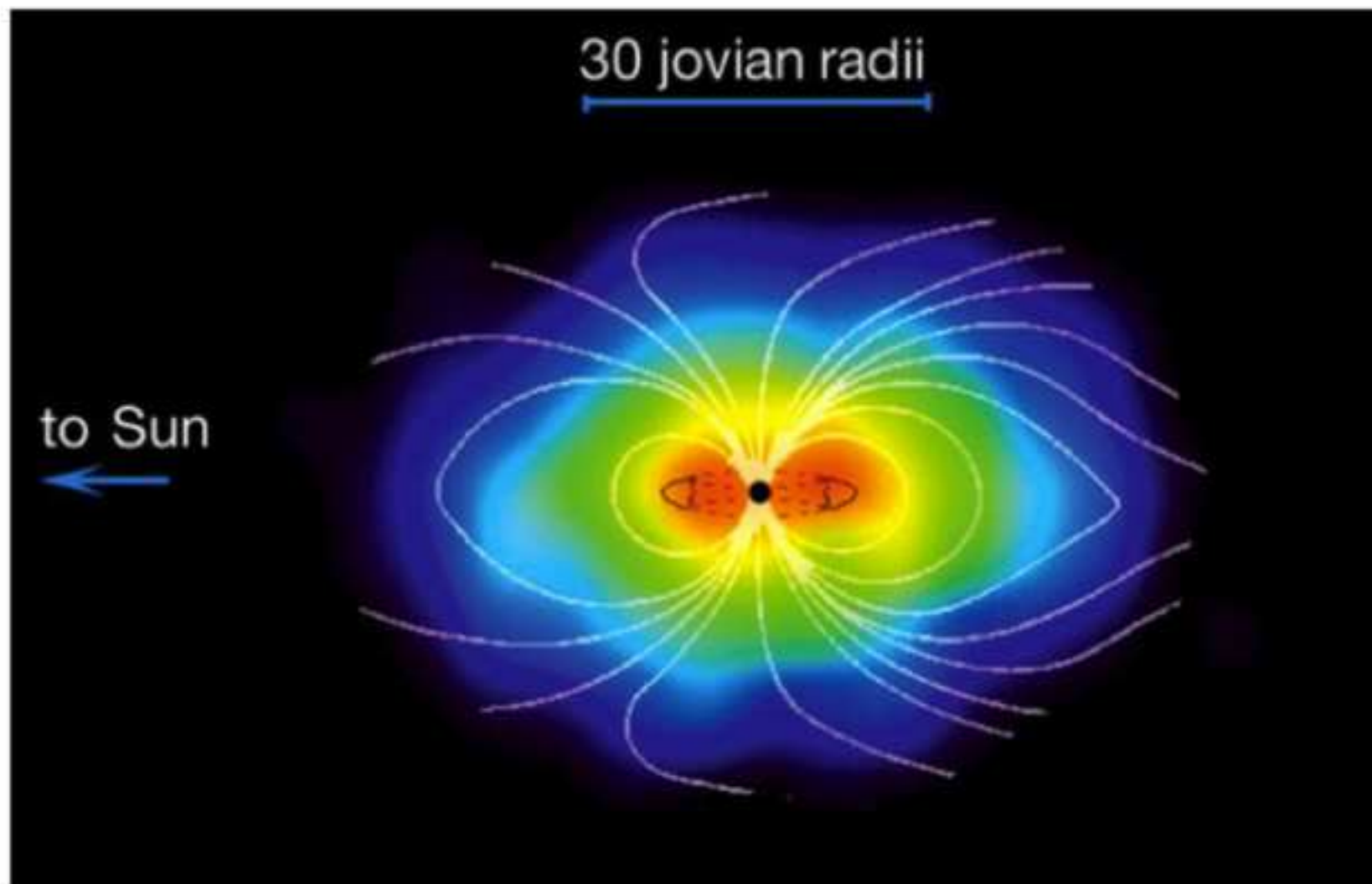


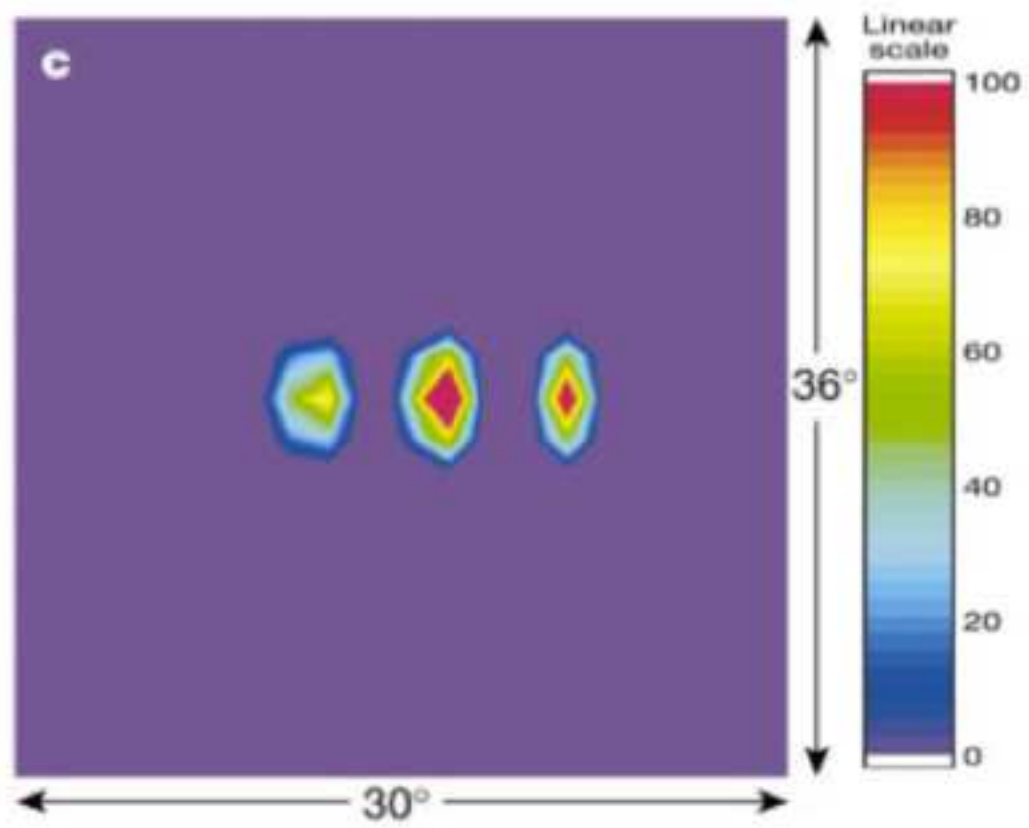


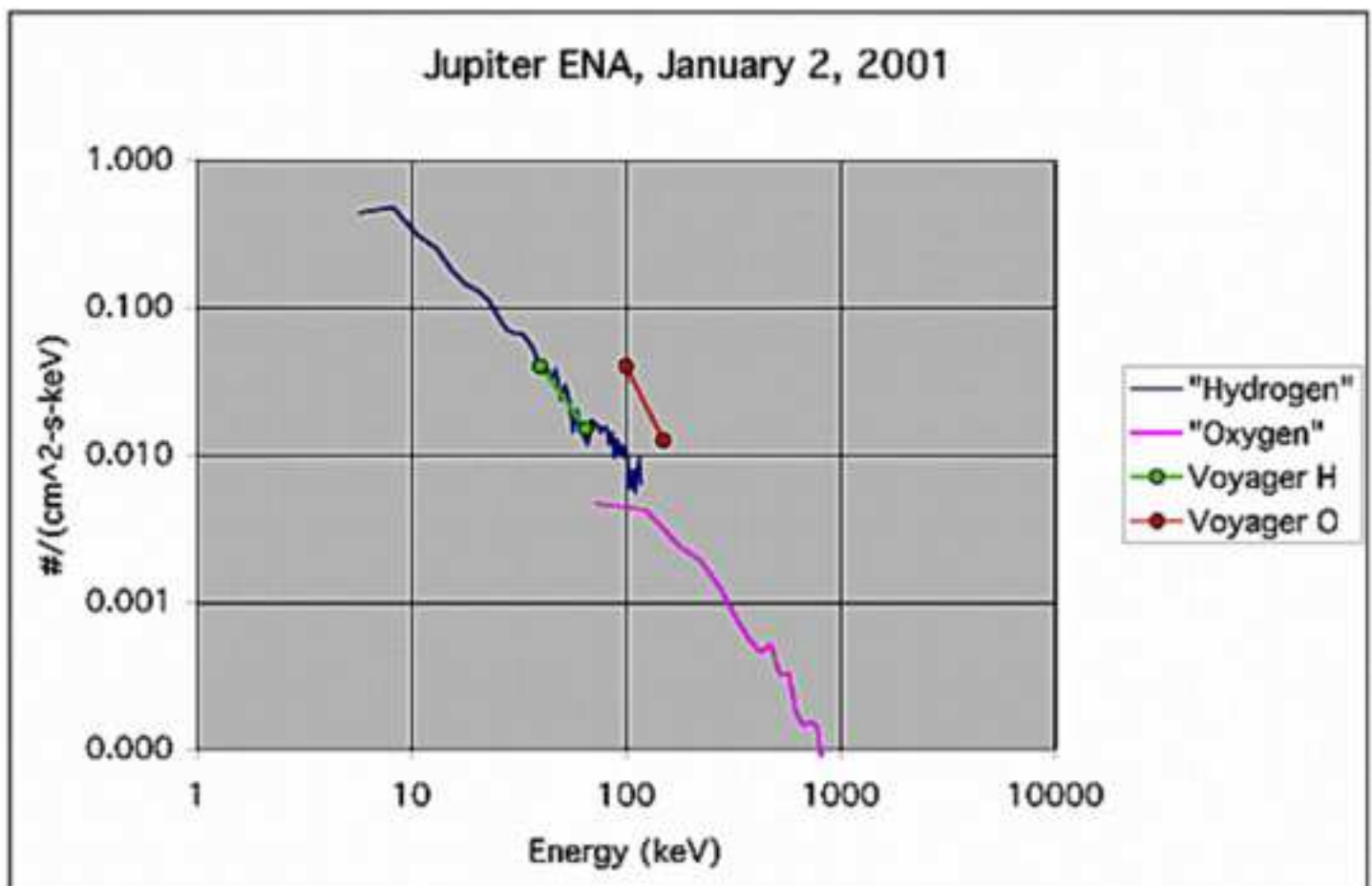
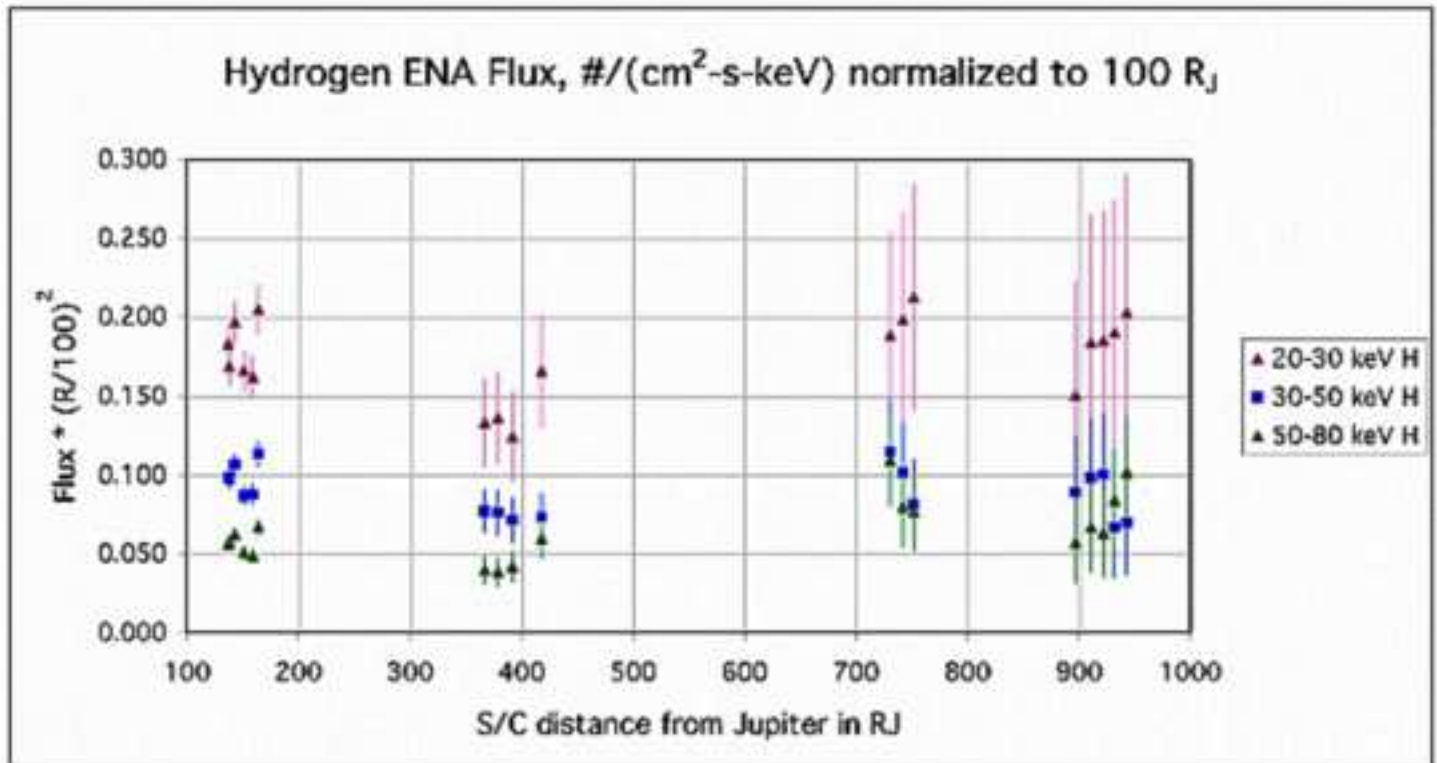








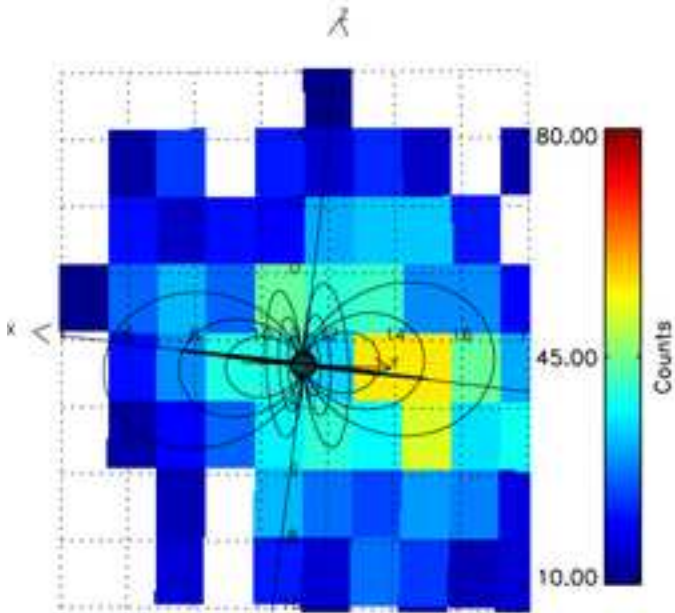




(a) Observed

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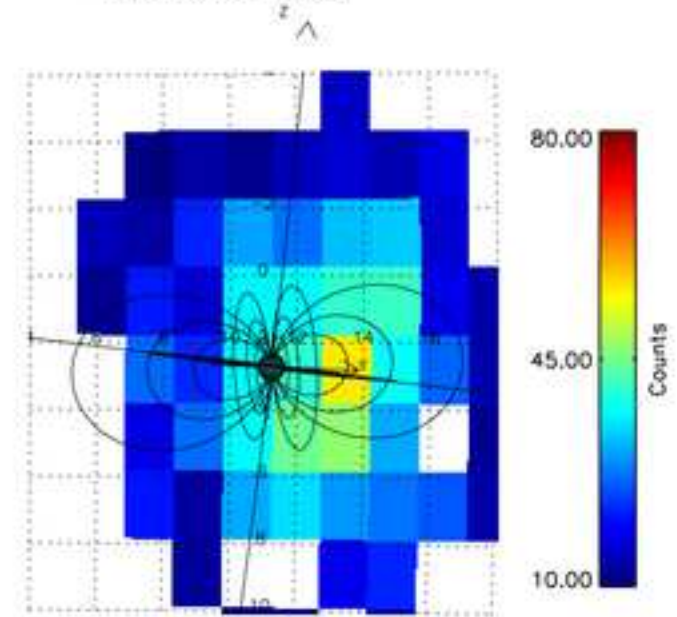
Hydrogen 55- 90 keV



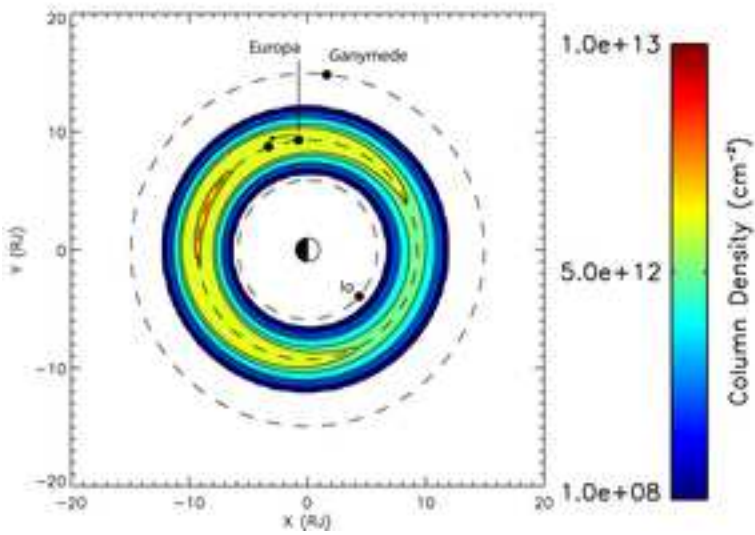
(b) Simulated - Asymmetric Cloud

2001002T15:18 UTC

Hydrogen 55- 90 keV



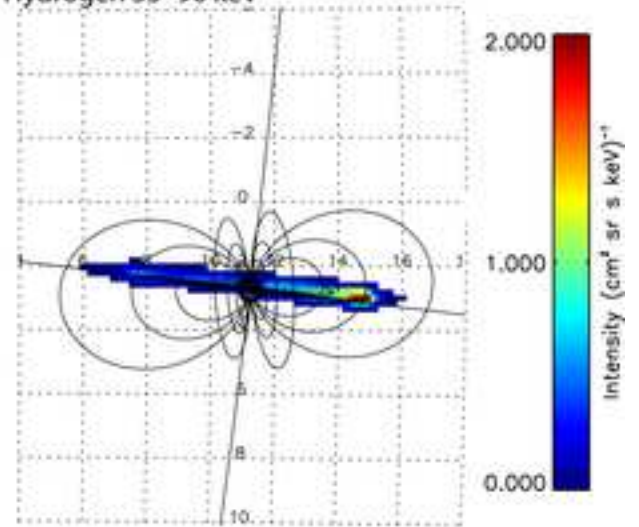
(c) Model Neutral H₂ Distribution

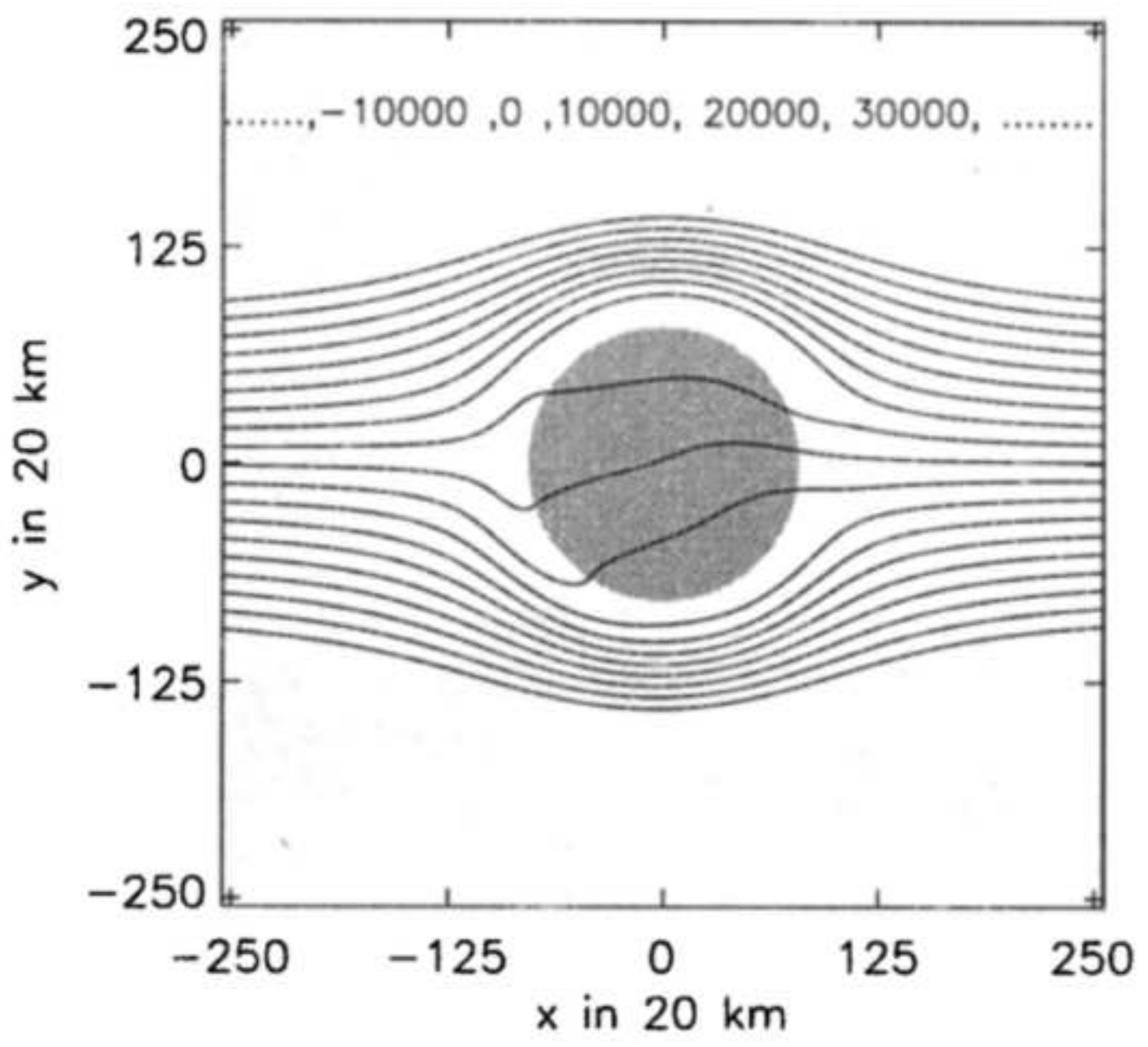


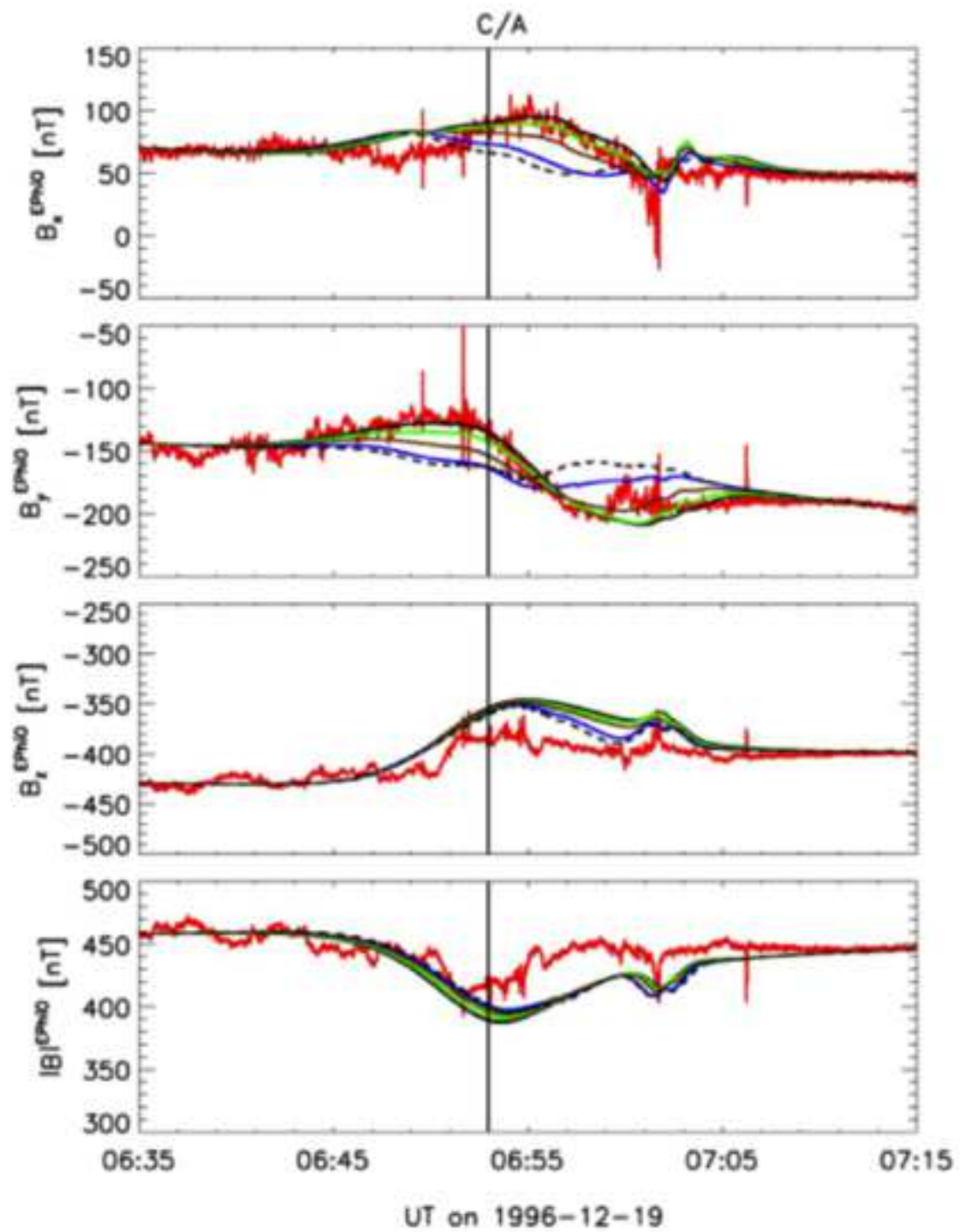
(d) Simulated - No PSF

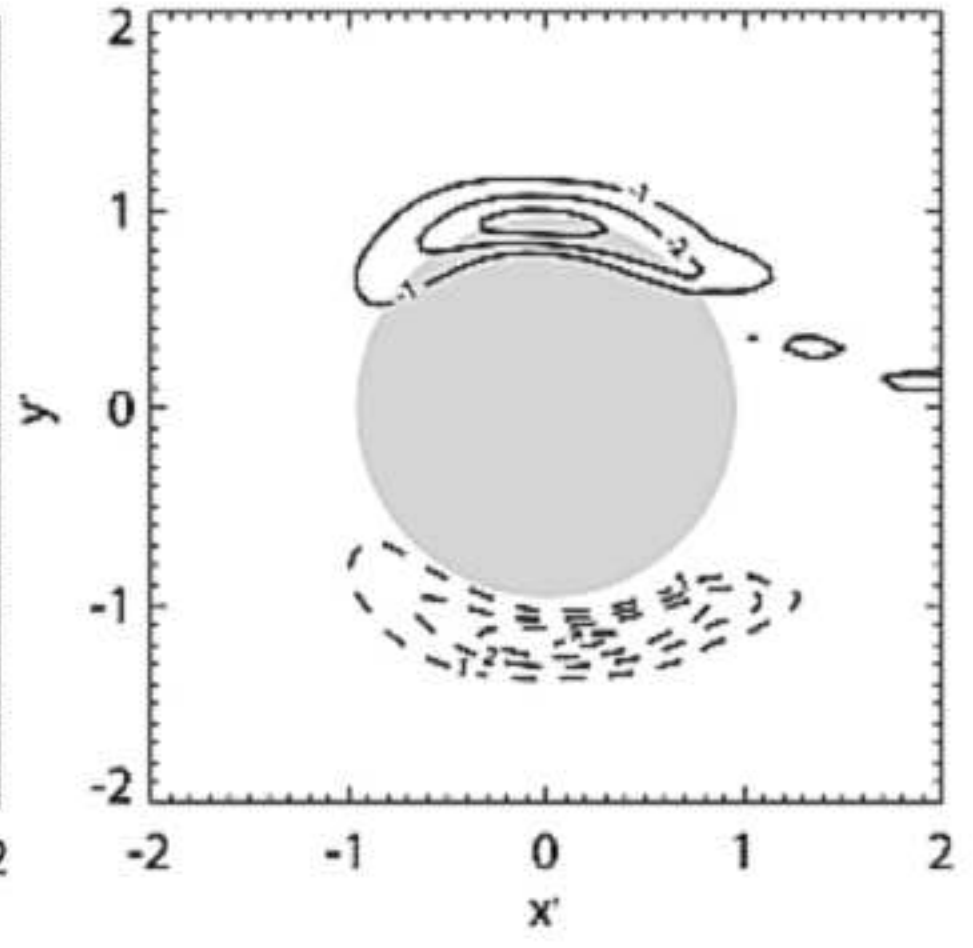
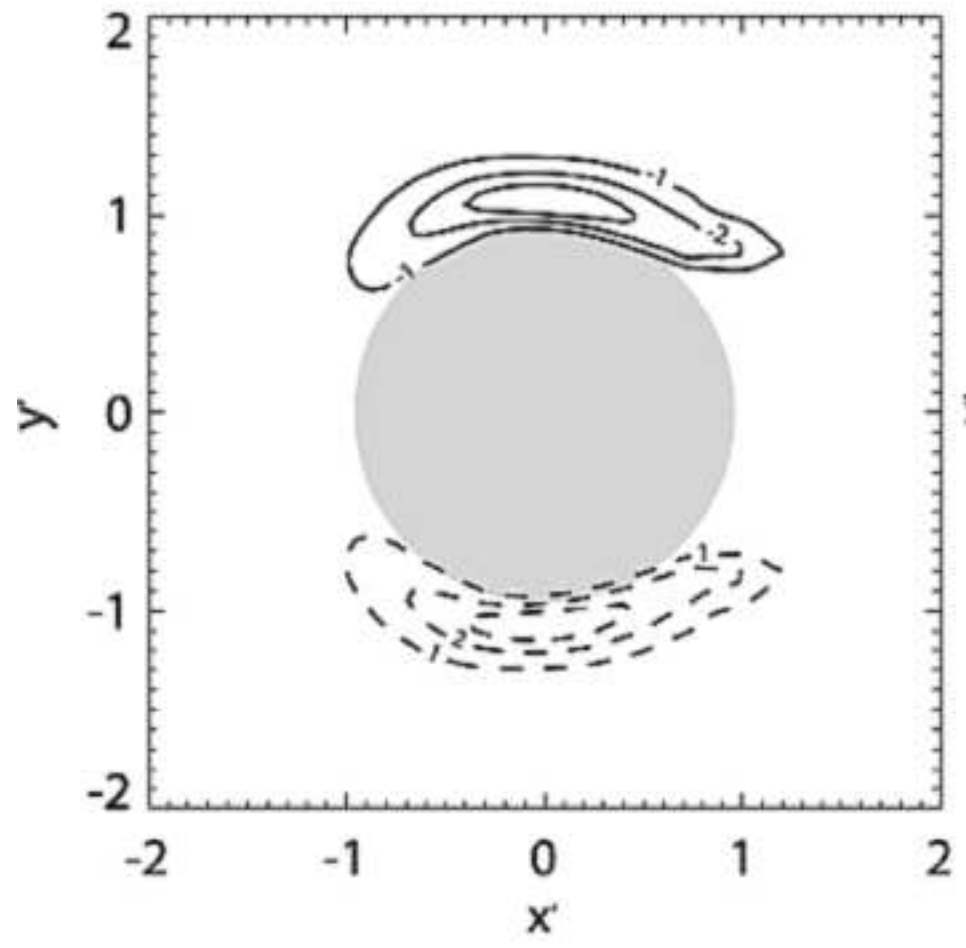
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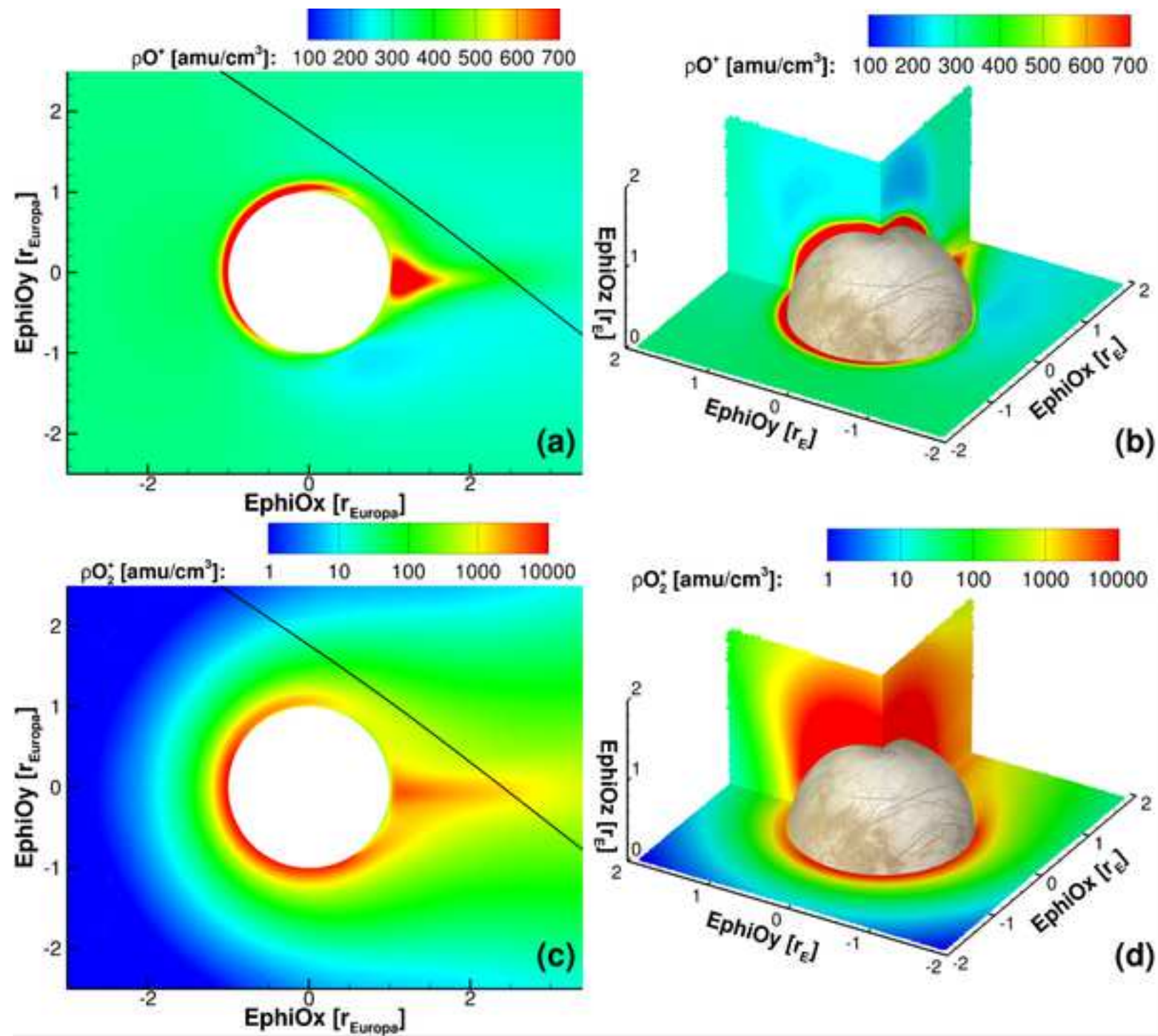
Hydrogen 55- 90 keV

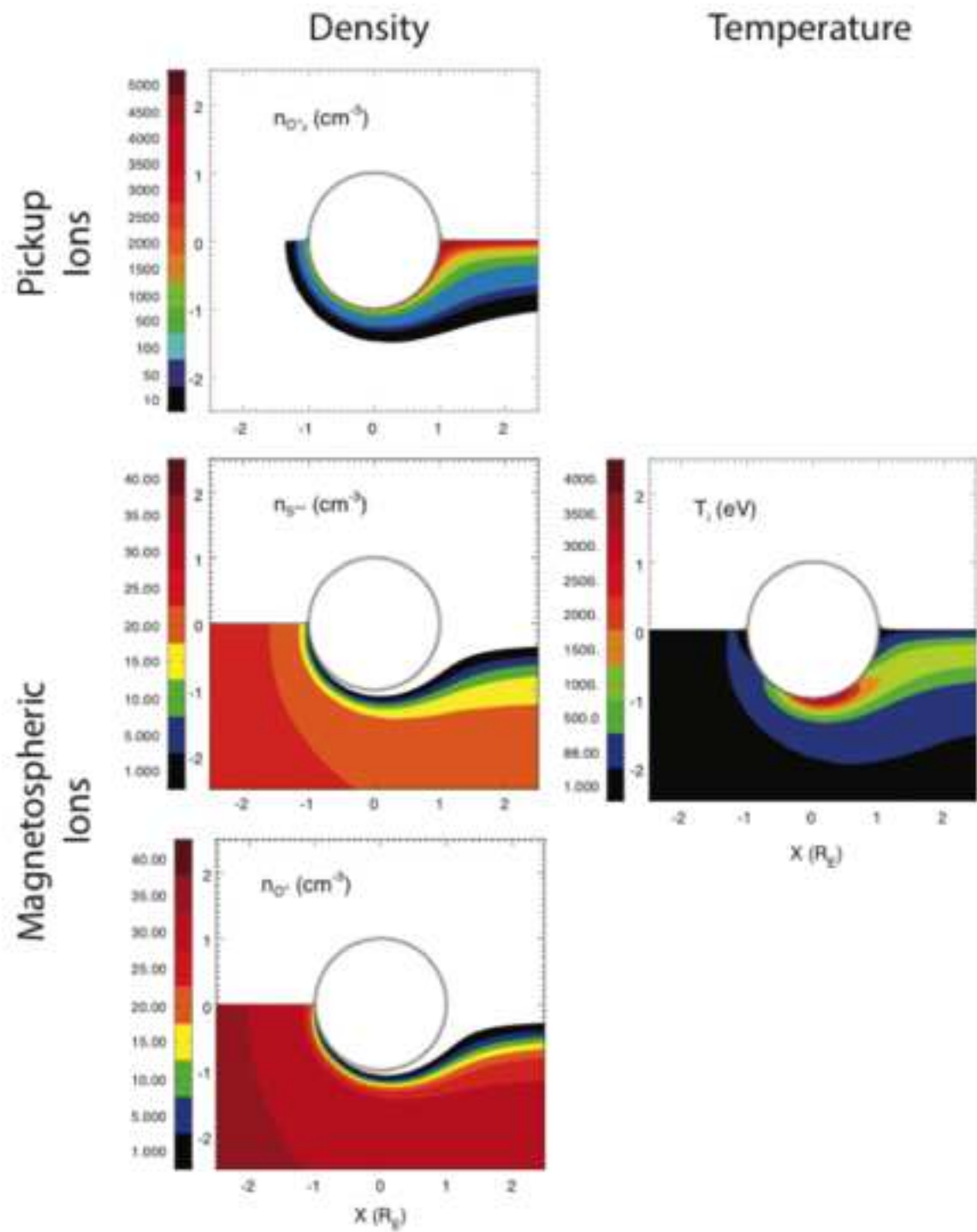


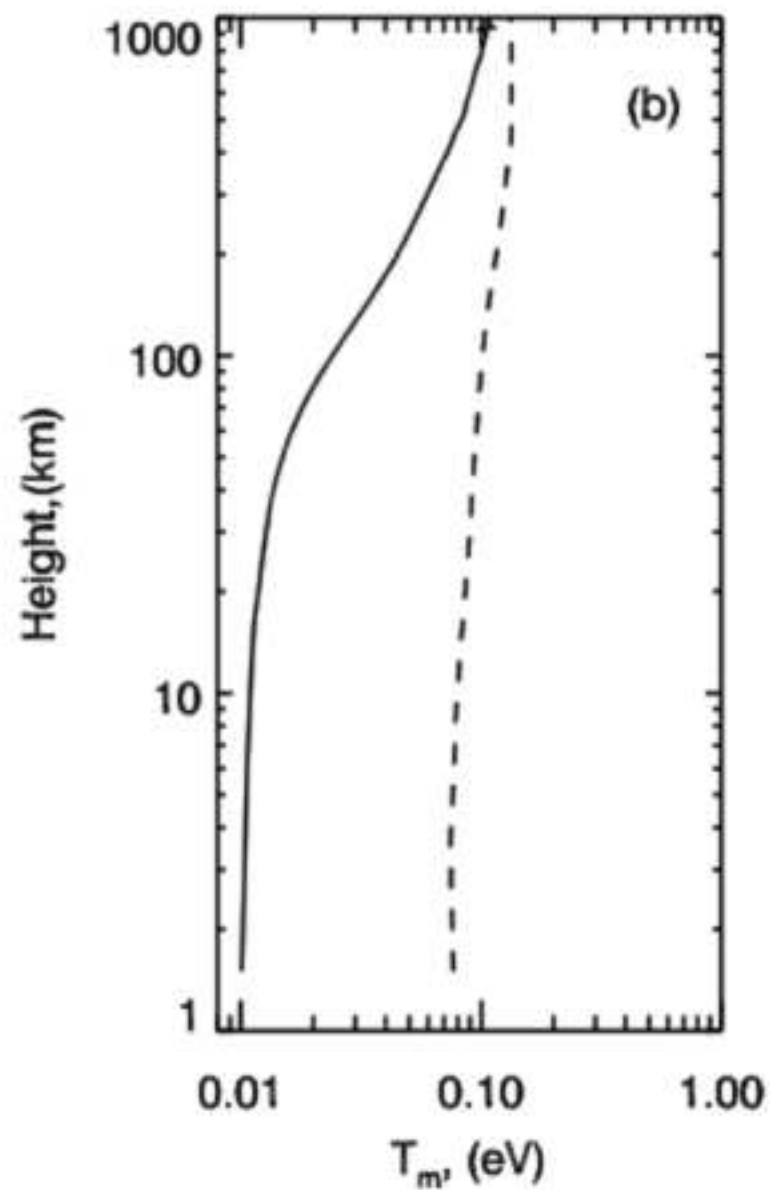
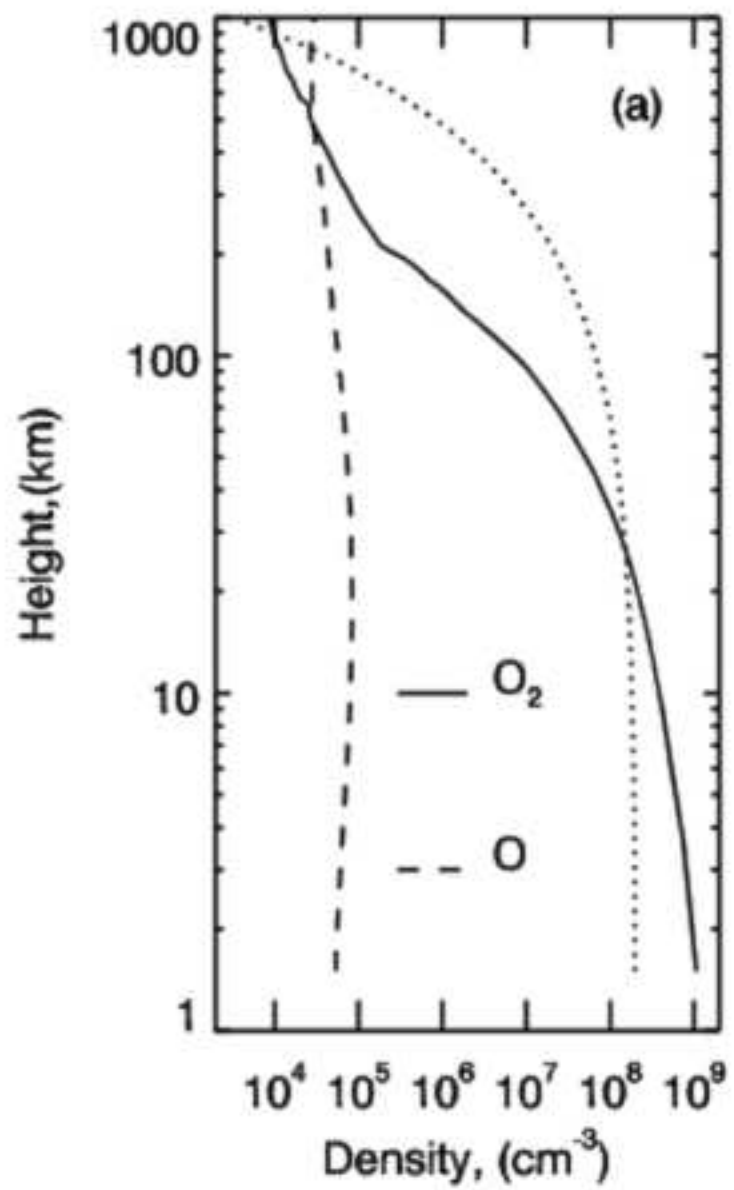


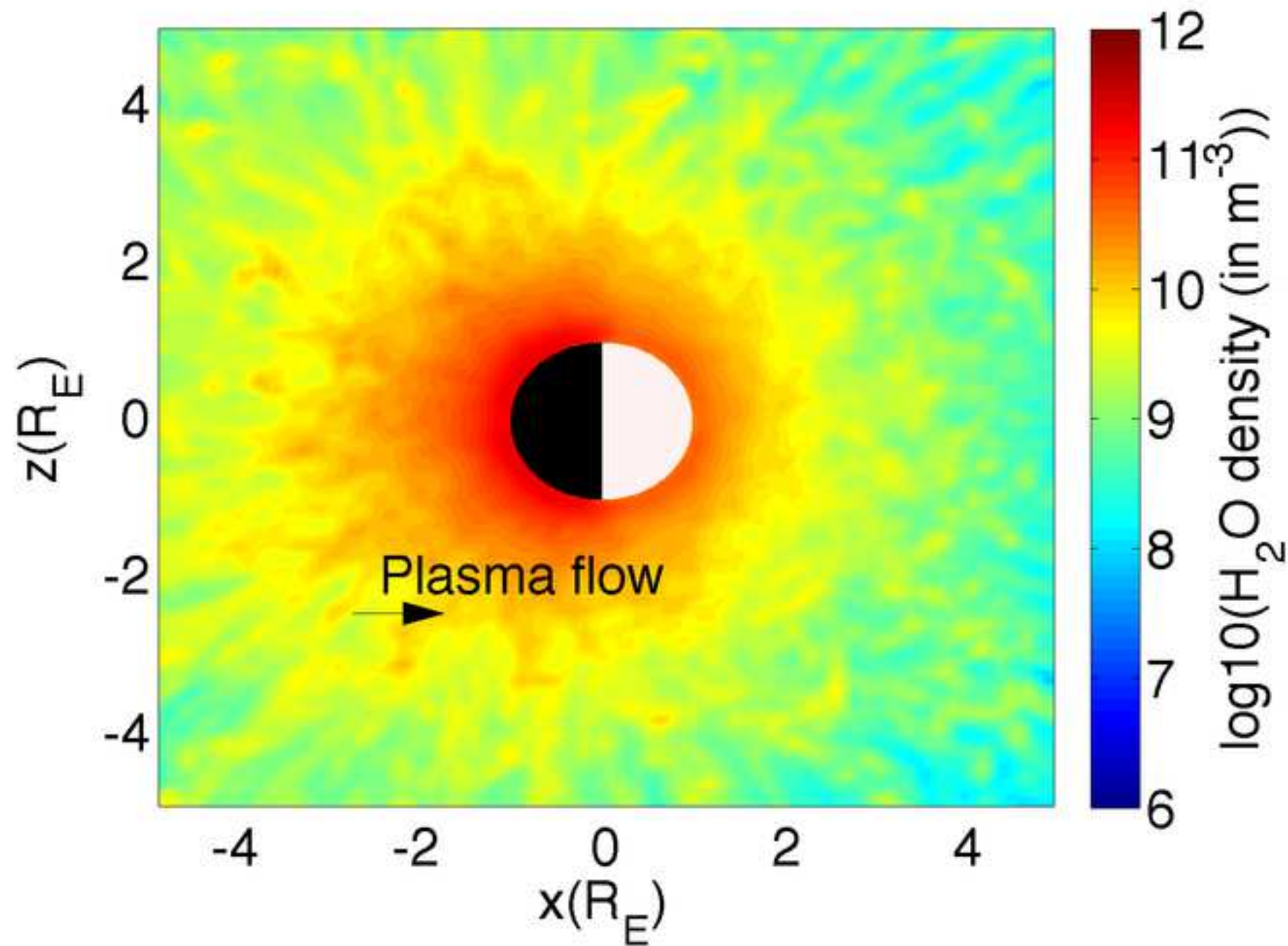


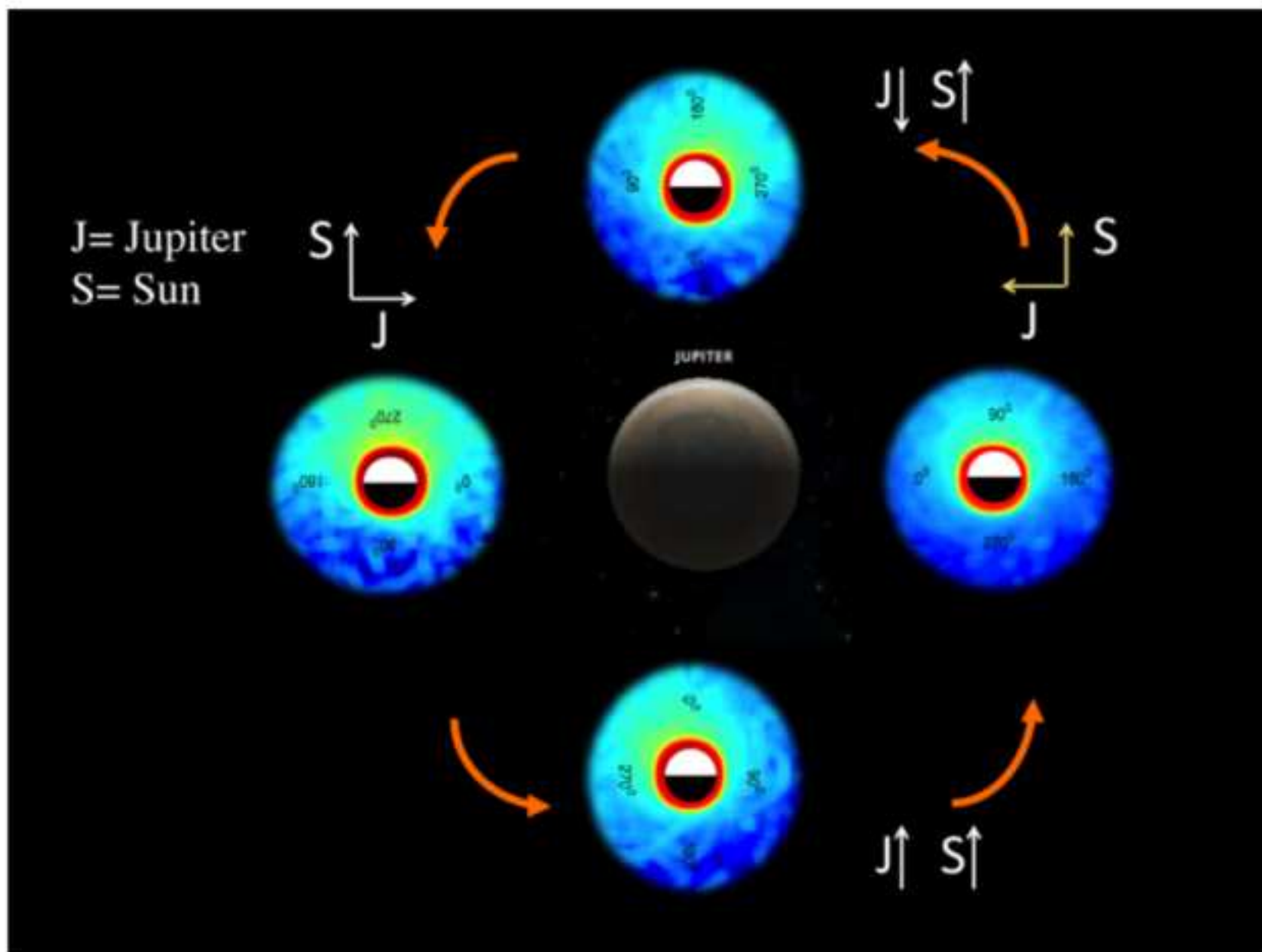


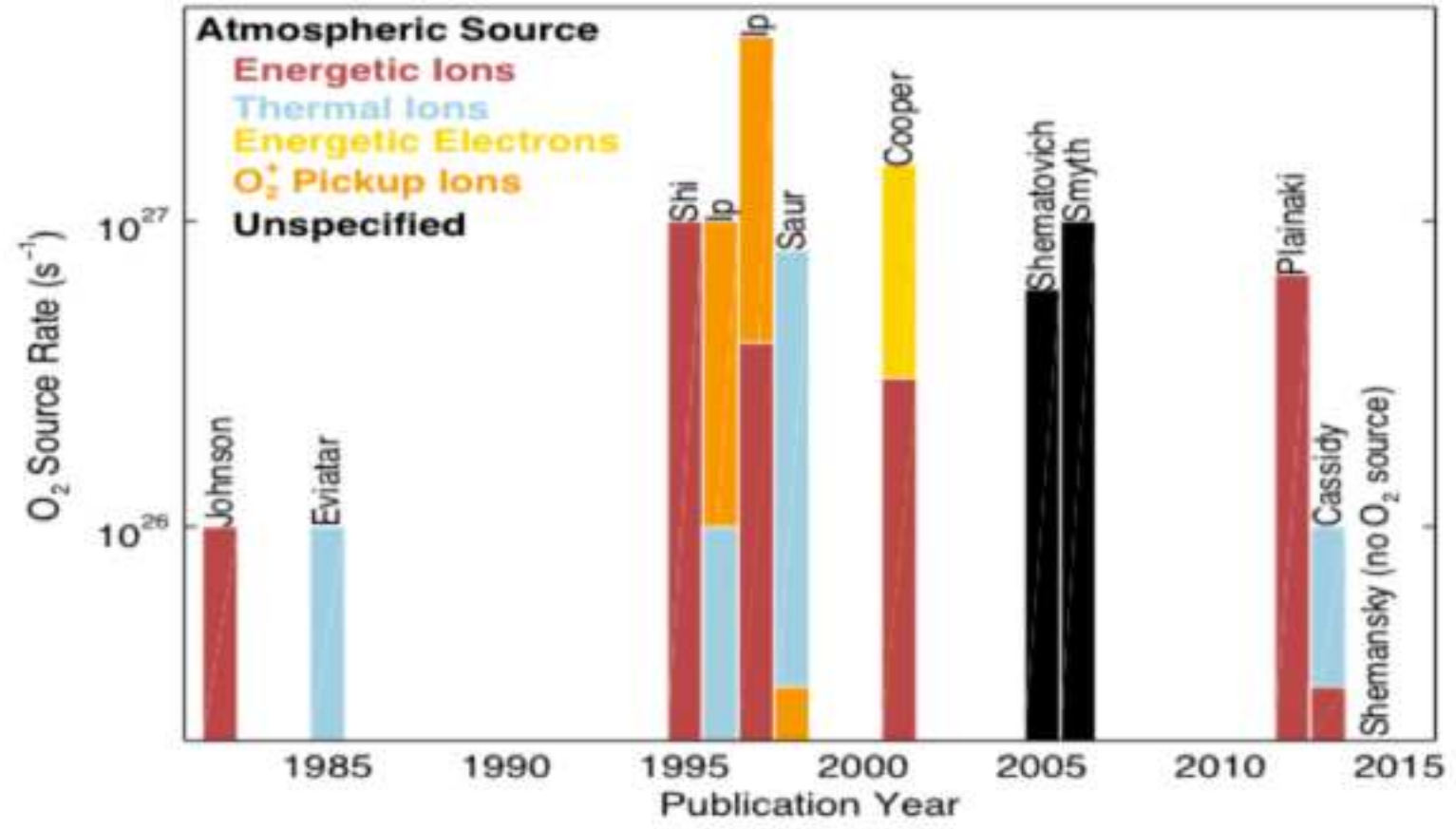




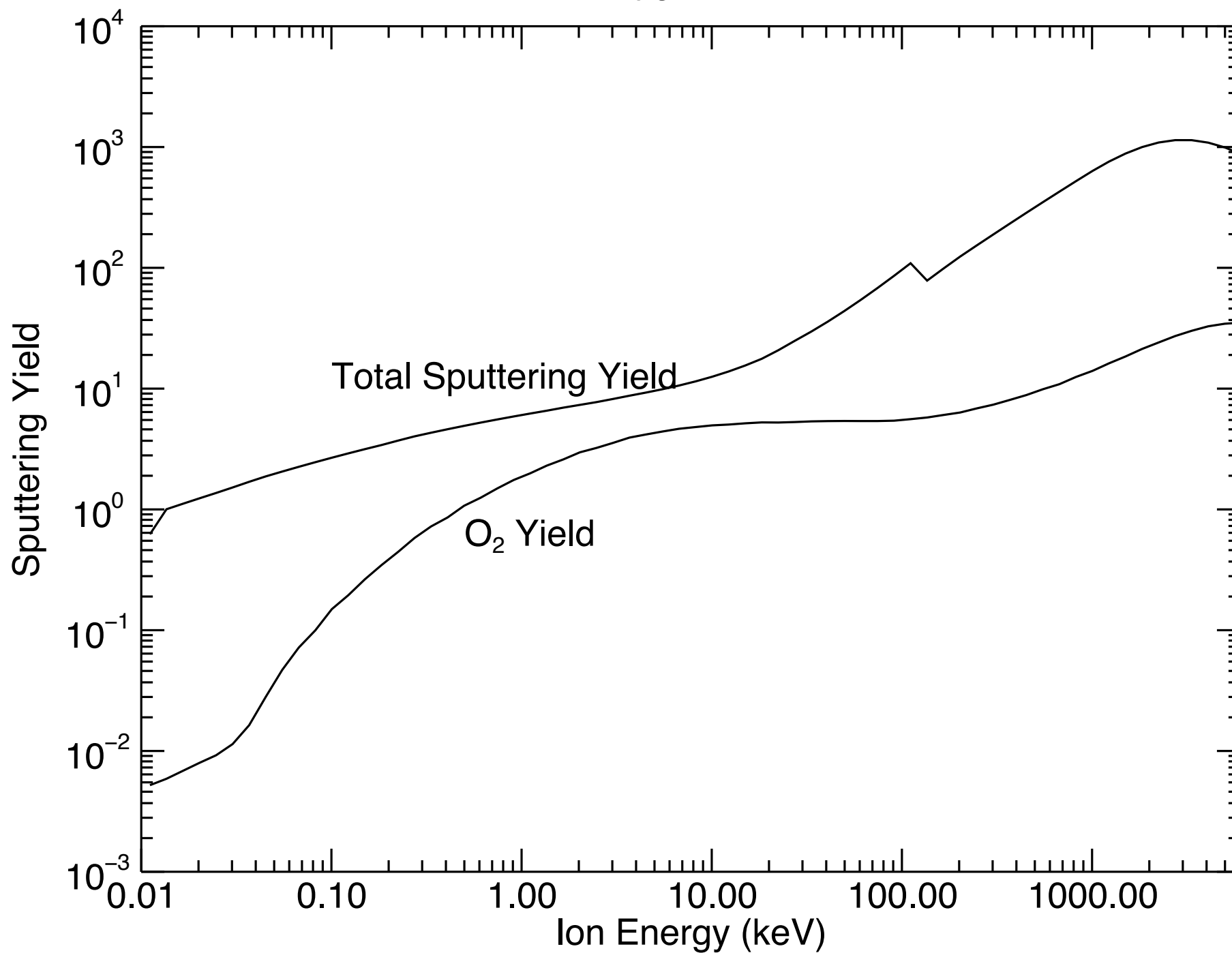








Oxygen Ions



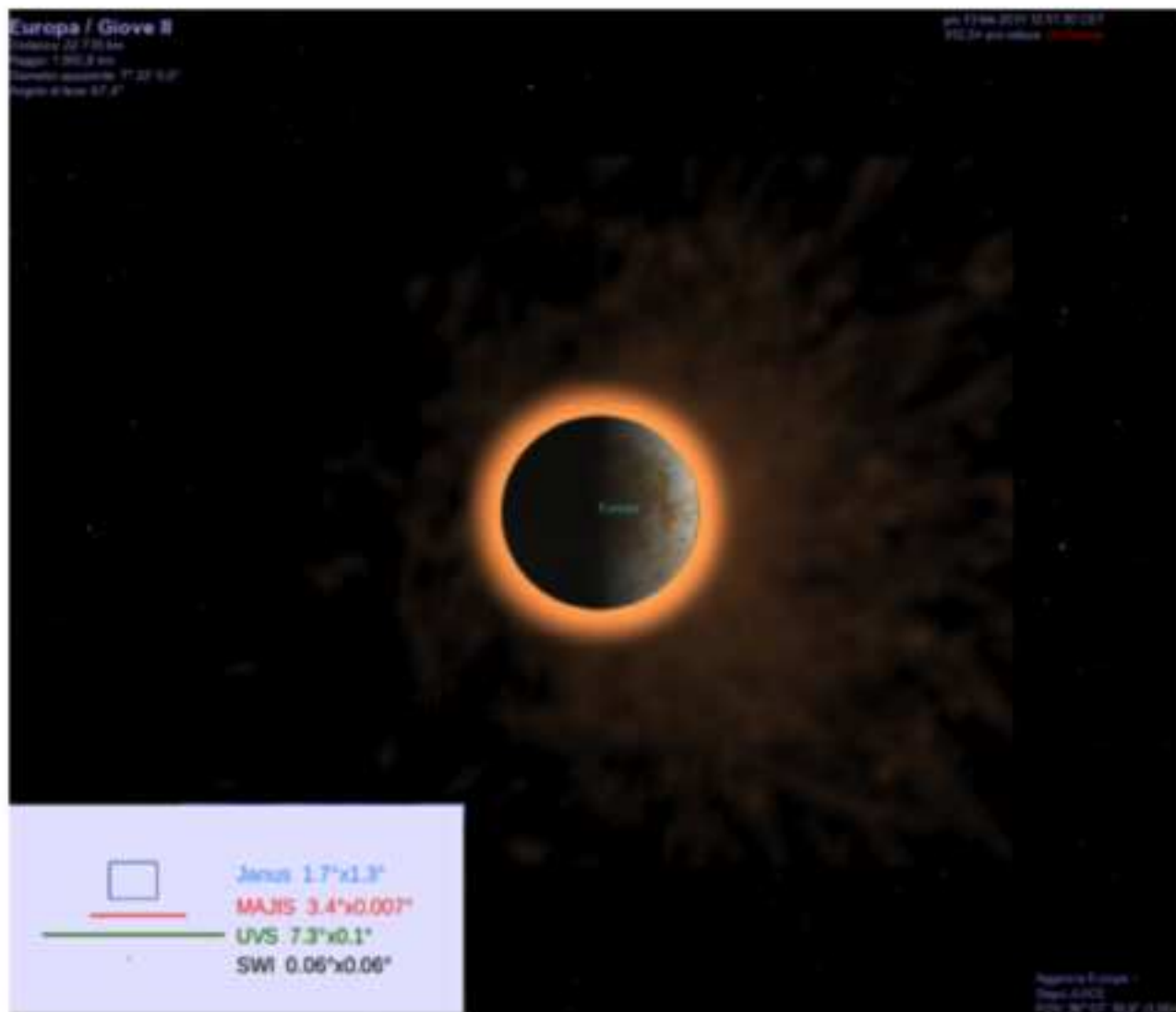


Table 1: Overview of the observations of Europa's tenuous atmosphere

Oxygen atmosphere	Related publications	Years	Obs. days / visits	Total integration time	Main findings on Europa's atmosphere
HST/GHRS *	Hall et al. 1995; 1998	1994 / 1996	3	337 min	- First detection of oxygen atmosphere- - O ₂ main species
HST/STIS #1 *	McGrath et al. 2004	1999	1	156 min	- First images of oxygen emissions - Irregular oxygen aurora morphology
Cassini UVIS *	Hansen et al. 2005 / Shemansky et al. 2014	2001	2	967 min	- Extended atomic oxygen cloud
NH/Alice	Retherford et al. 2007	2007	~6	104 min	- Confirm ratio of 2 for O ₂ main species
HST/ACS	Saur et al. 2011 / Sparks et al. 2010 / Retherford et al. 2007	2007 - 2008	3	343 min	- Correlation of oxygen brightness to Europa's magnetospheric position (Saur et al. 2011)
HST/STIS #2	Roth et al. 2014a,b; 2016	2012 / 2014 - 2015	19	2639 min	- Transient H ₂ O plume outgassing activity - Systematic correlation of aurora morphology and brightness to the magnetosphere - Consistently brighter dawn side aurora - Differing oxygen line ratio between upstream and downstream hemispheres - Oxygen aurora unchanged in eclipse
Trace species					
Mt. Bigelow *	Brown and Hill, 1996	1995	1	20 min	- First detection of sodium
Keck HIRES *	Brown 2001	1998	2	10, 20, 600, 1800 sec	- First detection of potassium, and contemporary measurements of sodium and potassium in the region 5-15 R _E - First Na/K ratio (similar to cosmic abundance)
Keck HIRES *	Leblanc et al. 2002	1999	1	4, 15 min	- Sodium vertical profiles up to 40 R _E
KPNO McMath*	Leblanc et al. 2005	2000	3	600, 1800 sec	- Sodium velocity profiles
Cassini ISS *	Porco et al. 2003 / Cassidy et al. 2008	2001			- Visible auroral emissions in eclipse detected
HST/FOS	Horst and Brown 2013	1994	2	35, 924, 1100 sec	- No detection of Magnesium, only upper limit

*see McGrath et al. 2009 for a more detailed review of these observations

Table 2: Comparison among the plasma model assumptions.

	Saur et al. (1998)	Kabin et al. (1999)	Liu et al. (2000)	Schilling et al. (2007, 2008)	Rubin et al. (2015)
Modeling approach	Numerical solution to Ohm's law, 3D two-fluid plasma model, fixed B field	3D single-fluid MHD model	2 species ideal MHD model	3D single fluid MHD	3D multifluid MHD
Simulation domain	Cartesian grid with 20 km resolution	Cartesian grid variable grid size.	Cartesian, extending $-192R_E \leq x \leq 64R_E$; $-128R_E \leq y \leq 128R_E$, variable grid size.	Cartesian, +/- 10 R_E extent in x-y plane, +/- 60 along z. Variable grid size.	Spherical, $-32 R_E$ to $32 R_E$ extent on all axes and variable grid size
Electron modeling	Separate magnetospheric and ionospheric electrons	Single electron population	Single electron population	Single electron population	Single electron population
Electron heat conduction	Included	Not included	Not included	Not included	Included
Modeled ion species	Single ion species stands in for both O^+ and O_2^+	Single ion species stands in for O^+ and O_2^+	Magnetospheric O^+ and pickup O_2^+	Single ion species stands in for O^+ and O_2^+	Magnetospheric O^+ and pickup O_2^+
Inner boundary conditions	Electric potential determined by ionospheric conductivity.	2 cases: perfectly conducting sphere and a perfectly absorbing sphere	Magnetospheric ion density set to 0, velocity set to 0, field set to sum of background Jovian and induced dipole.	Solid body is described by the concept of virtual plasma	Floating boundary condition; field inside of moon set to sum of background Jovian and induced dipole. Boundary permits plasma flow into surface.
Ocean induction	Not included: assumed constant homogenous Jovian background field (not self-consistent)	Included	Included	Included	Included
Neutral atmosphere model (surface density, scale height, column density)	single fluid of O_2 molecules, asymmetric atmospheric surface dens. (ratio surface density trailing/leading hemisphere~2.3), $H=150$ km, column density: $5 \cdot 10^{18} m^{-2}$	None	hydrostatic O_2 atmosphere (surface dens.: $2.85 \cdot 10^7 cm^{-3}$, scale height: 175 km, column density: $5 \cdot 10^{18} m^{-2}$)	Similar to Saur et al.	Similar to Saur et al., but includes two scale heights to model extended atmospheric corona.
Ionization source and total rate	Electron impact ionization	Electron impact ionization	Electron impact ionization	Electron impact ionization	Electron impact ionization
Collisions between particles	Ion-neutral collisions	Ion-neutral collisions	Estimated to be negligible	Ion-neutral collisions	Ion-neutral
Plasma loss	Dissociative recombination, absorption by moon, and, implicitly, charge exchange	Dissociative recombination and absorption by moon	Dissociative recombination and absorption by moon	Dissociative recombination	Dissociative recombination and absorption by moon
modeled data	HST oxygen emission observations	E4	E4 (density, plasma temperature, speed, magnetic field)	E4 (magnetic field)	E4, E26

Table 3: Comparison among the atmosphere model assumptions.

	Ip et al. 1996; 1998	Saur et al. 1998	Shematovi ch and Johnson 2001	Shematovi ch et al. 2005	Tiscar eno and Geissl er 2003	Smyth and Marconi 2006	Cassidy et al. 2007	2009	Plainaki et al. 2012; 2013; Milillo et al. 2016	Wurz et al. 2014	Shemansky et al. 2014
Validity range (vertical altitude coverage)	6 R _E	Up to a few Europa radii	up to ~1000 km from the surface	up to ~1000 km from the surface	N/A	up to ~1000 km from the surface	8R _E	400 km	up to 4 R _E ; infinity (Hill radius) (2016)	exobase - infinity (Hill radius)	not described
Spatial resolution	Not specified	20 km	1.5 km	1.5 km	10° latitude	Not described	N/A	N/A	0.1R _E	> 1km (variable : > mean free path)	not described
Included species	H ₂ O, O ₂ , H ₂	O ₂	O ₂ and O	H ₂ O, OH, O ₂ , O, H ₂ , H	H ₂ O	O ₂ , H ₂ O, H ₂ , OH, O, H	O ₂	H ₂ O, Na, CO ₂ , SO ₂	H ₂ O, O ₂ , H ₂	H ₂ O, OH, O ₂ , O, H, H ₂ , various volatiles, various minerals	O ₂ , H ₂ O, H ₂ , OH, O, H
Included source process:											
<i>surface sputtering</i>	Yes	yes	yes	yes	yes	yes	yes	yes	Yes	Yes	Yes
<i>radiolysis</i>	No	no	no	yes	no	yes	yes	no	Yes	Yes	No
<i>sublimation</i>			no				no	yes	Estimation	Yes	
<i>PSD</i>	No	no	no	no	no	no	no	no	No	Yes	No
<i>MIV</i>	No	no	no	no	no	no	no	no	Estimation	Yes	No
<i>O₂⁺ dissociative</i>	No	no	yes	yes	no	no	no	no	No	no	yes

<i>recombination</i>											
<i>Other</i>	pickup-ion sputtering (1996)	Adjustable source rate	Yes (O ₂ , photo- and electron impact dissociation)	Yes (H ₂ O, O ₂ , and OH photo- and electron impact dissociation)							Includes process called "Exchange sputtering"
Included Loss processes											
<i>Ionization/dissociation from particles (ions, e)</i>	yes	yes	Yes,	Yes,	yes	yes	yes	yes	Yes	ions: no, e: yes	yes
<i>Elastic collisions (moment transfer) between magnetosph. ions and neutrals</i>	no	yes	yes	yes	no	yes	no	no	No	No	yes
<i>Ionization/dissociation from UV photons</i>	no	No (estimated to be negligible)	yes	no	no	no	yes	yes	No	Yes	no
<i>Charge exchange with magnetospheric ions</i>	no	yes	yes	yes	no	yes	no	no	Estimated	No	yes
<i>Charge exchange with pickup ions</i>	no	no	Yes	yes	no	no	no	no	No	No	No
<i>Particle multiple bouncing</i>	O ₂ , (1998)	O ₂	O ₂ ,	O ₂ , H ₂	No	O ₂ , H ₂	O ₂	O ₂ , H ₂	O ₂ , H ₂	No	No
<i>Gravitational escape</i>	Yes (1996)	no	Yes	yes	yes	yes	yes	yes	Yes	Yes	No
Radiation pressure	no	no	No	no	no	no	no	no	No	No	No

Neutral/Neutral collisions	no	no	Yes	yes	no	yes	no	no	No	No	No
Chemistry included	no	no	No	no	no	yes	no	no	No	No	yes
Dimensionality	2D	3D	1D spatial configuration, 3D velocity space configuration	1D spatial configuration, 3D velocity space configuration	2D	1D	3D	3D	3D	1D spatial configuration, 2D velocity space config.	1D
Orbital configuration	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	O ₂	Not specified	Not specified
Surface release yield	Variety of experiments from mid-1980s and Johnson (1990) www.people.virginia.edu/~rej	N/A	free parameter	free parameter	Shi et al. (1995), Johnson (1990)	free parameter	free parameter	Johnson 1990 www.people.virginia.edu/~rej	Famà et al. 2008 formula	Cassidy et al. (2010), Shi et al. (1993), and Famà et al. (2008)	Aumayr and Winter (2004), Shemansky (2003)
Energy Distribution Function	O ₂ sputtering distribution, thermal accommodation	N/A		H ₂ O and O ₂ sputtering distribution, thermal accommodation	H ₂ O sputtering distribution	not described	O ₂ sputtering distribution, thermal accommodation	See paper	<u>H₂O</u> : sputtering distribution (Sigmund, 1969); O ₂ , H ₂ : Johnson et al., 1983. Thermal accommodation for O ₂ and H ₂ re-impacting the surface	<u>H₂O</u> : sputtering distribution (Sigmund, 1969; Wurz and Lammer 2003); Sublimated <u>H₂O</u> : Maxwellian distribution;	not described

										PSD-ed H_2O : Johnson (2002)	
Plasma Flow Geometry	2D MHD solution to flow around cylinder	2D electric field calculation. Fixed B field.	Not applicable	Not applicable	Lunar-like	Lunar-like	Lunar-like	Lunar-like	Lunar-like	Not applicable	Lunar-like
Model free (tunable) parameters	Not specified	O ₂ surface density/depletion length scale	Not specified	Source rate	Ion bombardment pattern	Source rate	Sticking coefficient, source rate	N/A	energetic ion spectrum, precipitation map, surface Temperature, orbital position	Not specified	Not specified

Table 4: Comparison among the atmosphere model outputs

	Ip et al. 1996; 1998	Saur et al. 1998	Shematovich and Johnson 2001	Shematovich et al. 2005	Tiscareno and Geissler 2003	Smyth and Marconi 2006	Cassidy et al. 2007	2009	Plainaki et al. 2012; 2013; Milillo et al. 2016	Bern model	Shemansky et al. 2014
Density spatial distribution H₂O	no	Not applicable	Not applicable	average case	2D	1D	Not applicable	3D	3D	1D	Not applicable
Density spatial distribution O₂	2D (1996)	3D	average case	average case	Not applicable	1D	3D	no	3D	1D	Not applicable
Density spatial distribution H₂	no	Not applicable	Not applicable	Average case	Not applicable	1D	Not applicable	no	3D	1D	Not applicable
Density spatial distribution minor species	Not applicable	Not applicable	average case (O)	average case (O, OH)	Not applicable	1D	Not applicable	3D	Not applicable	1D	average case (O)
Near-surface O₂ scale height	~20 km	145 km	~ 20 km	~ 20 km	Not applicable	~ 20 km	~ 20 km	Not applicable	~ 20 km	~20 km (sublimated) ~600 km (sputtered)	Not applicable
Neutral supply to the torus	Yes (1998)	no	Yes (O)	Yes (H,H ₂ ,O)	yes (H ₂ O)	yes	no	no	Yes	yes	No
Ion supply to the magnetosphere (mass loading)	yes	yes	yes	yes	no	no	no	no	Yes	yes	No
Energy spectrum of the released neutrals	no	no	yes	yes	yes	no	no	yes	Yes	yes	No

Table 5: Interdisciplinary science goals, objectives and requirements related to the Europa atmospheric science

Notes: The JUICE Science Objectives related to Europa as defined in the Red Book, were numbered as follows: 1. Determine the composition of the non-ice material at Europa, especially as related to habitability; 2. Search for liquid water under the most active sites at Europa; 3. Study the recently active processes at Europa; 4. Understand the moons as sources and sinks of Jupiter's magnetospheric plasma.

Interdisciplinary Science Goal of the current proposal	Science objective of the current proposal	Related JUICE Science Objectives	Requirements	
			JUICE Payload Instruments in simultaneous operation	Notes
G1. Characterization of the atmospheric environments of Europa	G1.1. Identify the local composition and determine the density spatial and energy distribution of the main constituents of Europa's exosphere	1;3	JANUS, MAJIS, PEP-JDC, PEP-JNA, PEP-NIM, SWI, UVS	phase 2.b (Europa flybys)
	G1.2. Search for residuals in the exosphere of recent plume activity	2;3		
G2. Investigation of the interactions between the tenuous atmosphere of Europa and the Jovian magnetosphere, with respect to the relation between the time-scales of their variations	G2.1. Determine the neutral escape and the ion-supply to the Jovian magnetosphere	4	PEP-JDC, PEP-JEI, PEP-JNA, PEP-JoEE, RPWI	phase 2.b (Europa flybys)
	G2.2. Identify the variability of Europa's gas cloud with changes of the Jovian plasma conditions and to the moon's induced magnetic field	4	J-MAG, PEP-JDC, PEP-JoEE, PEP-JEI, PEP-JENI, RPWI, UVS	phase 2.b (Europa flybys) phase 2.c (Jupiter inclined orbit)?
	G2.3. Determine the role of Io in supplying plasma to the tenuous atmosphere of Europa and investigate the related temporal variability	4	MAJIS, PEP-JENI, RPWI, UVS	phase 2.c (Jupiter inclination orbit)
G3. Study of the moon atmosphere - surface coupling as a main agent for both the exosphere generation and surface weathering	G3.1. Determine local plasma composition at Europa above the surface regions with major concentration in non-icy components; determine their relation with the exosphere composition	1; 2; 3	MAJIS, PEP-JDC, PEP-JEI, PEP-JNA, PEP-JoEE, PEP-NIM, RPWI, SWI, UVS	phase 2.b (Europa flybys)
	G3.2. In case of the existence of plumes at Europa, identify their implications to the moon's local surface composition	2; 3	JANUS, MAJIS, PEP-NIM, UVS	phase 2.b (Europa flybys)