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First 3D test particle model of Ganymede’s ionosphere

G. Carnielli^{a,*}, M. Galand^a, F. Leblanc^b, L. Leclercq^c, R. Modolo^d, A. Beth^a, H. L. F. Huybrighs^e, X. Jia^f

^a*Department of Physics, Imperial College London, SW7 2AZ, London, United Kingdom*

^b*LATMOS/IPSL, CNRS, Sorbonne Université, UVSQ, Paris, France*

^c*University of Virginia, Charlottesville, Virginia, USA*

^d*LATMOS/IPSL, UVSQ Université Paris-Saclay, UPMC Univ. Paris 06, Guyancourt, France*

^e*ESA/ESTEC, Noordwijk, The Netherlands*

^f*Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109-2143, USA*

Abstract

1 We present the first three-dimensional multi-species ionospheric model for
2 Ganymede, based on a test particle Monte Carlo approach. Inputs include
3 the electromagnetic field configuration around the moon from the magneto-
4 spheric models developed by Leclercq et al. (2016) and by Jia et al. (2009),
5 and the number density, bulk velocity and temperature distributions of the
6 neutral exosphere simulated by Leblanc et al. (2017). According to our simu-
7 lations, O_2^+ is the most abundant ion species, followed by O^+ , H_2^+ and H_2O^+ .
8 For O^+ and O_2^+ , the majority of ions produced impact the moon’s surface,
9 while for the other species the majority escapes Ganymede’s magnetosphere.
10 For all ion species, the escape occurs either in the direction of corotation of
11 the Jovian plasma or through the Alfvén wings.

12 To validate our model, the output of our simulations, performed under the
13 Galileo G2 flyby conditions, are compared to the observations. These include
14 the electron density derived by the plasma wave instrument (PWS), the ion

*Principal corresponding author:

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Email address: g.carnielli@imperial.ac.uk

15 energy spectrogram measured by the plasma analyzer (PLS) and the associ-
16 ated plasma moments (Frank et al. (1997a)). On the one hand, the electron
17 density found by our model is consistently underestimated throughout the
18 flyby, being at least one order of magnitude lower compared to observations.
19 We argue that the prime reason for this discrepancy comes from the exo-
20 spheric density, which may be underestimated. On the other hand, we find
21 a remarkably good agreement between the modeled ion energy spectrogram
22 and that recorded by PLS, providing a validation of the test particle model.
23 Finally, we compare the modeled plasma moments along the G2 flyby with
24 those analyzed by Frank et al. (1997a). The data seems to be more consistent
25 with an ionosphere dominated by O_2^+ instead of H^+ or O^+ , as suggested pre-
26 viously in the literature. This supports our finding that O_2^+ is the dominant
27 ion species close to the surface.

Keywords: Ganymede, Ionospheres, Jupiter, satellites, Satellite,
atmospheres

1. Introduction

28 Ganymede is the largest amongst the Galilean satellites and the prime
29 target of the JUpiter ICy moons Explorer (JUICE) mission (Grasset et al.
30 (2013)). Besides being the largest moon in the Solar System, it is also the only
31 one known to generate a magnetic field which is strong enough to overcome
32 the background Jovian field (Kivelson et al. (1996, 1997)); thus, the moon
33 carves out its own magnetosphere inside that of Jupiter.

34 The moon's magnetosphere is shaped by the dynamic interaction between
35 its internal dipole field and the Jovian plasma which overtakes the moon from

36 the orbitally trailing hemisphere at a speed of around 140 km/s in the moon's
37 frame (Kivelson et al. (2004)). At Ganymede's orbital radius (~ 15 Jupiter
38 radii) the plasma sheet corotates with Jupiter with a synodic period of 10.5
39 hours. Due to the relative inclination between Ganymede's orbital plane and
40 the magnetic equatorial plane of Jupiter, the moon orbits periodically above
41 and below the plasma sheet. This causes a periodic change of the background
42 magnetic field and upstream plasma conditions. Several MHD and hybrid
43 models have been developed to study the interaction between Ganymede's
44 internal field and the Jovian plasma sheet (Jia et al. (2008, 2009); Ip and
45 Kopp (2002); Paty and Winglee (2006); Leclercq et al. (2016); Wang et al.
46 (2018)). The models show that the interaction between the sub-sonic and
47 sub-Alfvénic flow and the moon's magnetic field leads to the formation of
48 Alfvén wings at the poles and a region of closed magnetic field lines at lower
49 latitudes.

50 Past remote and in-situ observations of the moon provided evidence of
51 the existence of a thin atmosphere. Barth et al. (1997) reported on the de-
52 tection of hydrogen from the ultraviolet spectrometer (UVS) onboard the
53 Galileo spacecraft, while Hall et al. (1998) and Feldman et al. (2000) in-
54 ferred the presence of O and O₂ from observations of Ganymede's aurora
55 with the Hubble Space Telescope (HST). The exosphere is primarily formed
56 from surface sputtering and radiolysis by energetic Jovian ions in the polar
57 regions and by sublimation of the icy surface in the subsolar region. Several
58 exospheric models have been developed to describe the neutral environment
59 around the moon. Marconi (2007), Turc et al. (2014), Plainaki et al. (2015)
60 and Shematovich (2016) predicted an exosphere dominated by O₂ in the po-

61 lar region and by H_2O in the subsolar region, while the most recent model
62 of Leblanc et al. (2017) considered a low sublimation rate in the subsolar
63 region, making, O_2 the dominant species everywhere at low altitudes.

64 The ionosphere is formed by ionization of the neutral exosphere. This
65 occurs primarily by absorption of solar EUV radiation and electron impact
66 from the Jovian magnetosphere population. Kliore (1998) provided an upper
67 limit of 4000 cm^{-3} for the ionospheric density from a Galileo radio occul-
68 tation, while Eviatar et al. (2001) presented electron density profiles from
69 the Plasma Wave Science (PWS) instrument along the G1 and G2 flyby
70 trajectories, consistent with the upper limit of Kliore (1998). Frank et al.
71 (1997b) presented measurements of an ion outflow recorded by the Plasma
72 Science instrument (PLS) onboard Galileo. They interpreted it as H^+ leaving
73 Ganymede's magnetosphere, in agreement with the finding of the multi-fluid
74 MHD simulation of Paty et al. (2008), who found O^+ to have an energy be-
75 low the instrument threshold, leaving it undetected. Vasyliūnas and Eviatar
76 (2000) reinterpreted this population as being O^+ with four times the number
77 density and one quarter of the speed.

78 Previous ionospheric models include those from Eviatar et al. (2001) and
79 Cessateur et al. (2012). Both used a simplified chemical model and zero-
80 dimensional local rate equations to retrieve the ionospheric density profile.
81 These models rely on a number of too restrictive assumptions, such as the
82 lack of transport for Cessateur et al. (2012) and ion composition reduced to
83 O^+ and O_2^+ for Eviatar et al. (2001).

84 We have developed the first 3D model of Ganymede's ionosphere, which
85 generates 3D high resolution maps of the number density, bulk velocity and

86 temperature for different species in Ganymede’s ionosphere. The results from
87 our model can be used not only to make more realistic interpretations of
88 Galileo ionospheric data during Ganymede’s flybys, but also to support the
89 JUICE mission. In addition to providing support for the interpretation of
90 data that will come from the spacecraft, the results of our model can be used
91 for optimising the operation mode of some instruments such as the Radio
92 Plasma Wave Instrument (RPWI). Furthermore, our model provides a set of
93 results, such as the plasma distribution around the moon, which can be used
94 in magnetospheric models to improve on the short comings of assumptions
95 adopted, such as the spherically symmetric configuration of the ionospheric
96 plasma.

97 In Section 2, we describe the ionospheric model, including the algorithm
98 and the major drivers. In Section 3, we present the conditions assumed
99 for the simulation and the assumptions made. In Section 4, we present the
100 results of our simulations over selected regions. In Section 5.1, our results
101 are compared with Galileo observations during G2 and in Section 5.2 reasons
102 for differences are discussed. Section 6 highlights the main results and their
103 implications.

104 **2. The model**

105 The ionospheric model is based on a Monte Carlo approach, where test
106 particles, i.e., macro particles representing a certain physical number of ions,
107 are created and followed in the presence of electric and magnetic fields. The
108 simulation is undertaken on a spherical grid centered on Ganymede contain-
109 ing $100 \times 90 \times 180$ cells in the radial (r), polar (θ) and azimuthal (ϕ) directions,

110 respectively. The radial cells extend from the surface up to $6.7 R_g$ ($R_g \equiv$
111 Ganymede's radius $\equiv 2634.1$ km) with spacing between cells increasing with
112 altitude, while the cells in the polar and azimuthal directions are equally
113 spaced with a separation of 2° . A total of 7.1×10^7 test particles launched
114 was found to suffice in order to obtain statistically robust results.

115 The model has two main inputs which are read at the start of the simu-
116 lation:

- 117 • the electric and magnetic fields around Ganymede, defined on a square
118 grid with a resolution of 125 km between $|X|$, $|Y|$ and $|Z| \leq 4 R_G$ and
119 of 250 km between $4 R_G < |X|$, $|Y|$, $|Z| < 8 R_G$. These are outputs
120 of the hybrid model developed by Leclercq et al. (2016) and applied to
121 the Ganymede environment;
- 122 • the neutral number density, bulk velocity and temperature of different
123 species from the exospheric model of Leblanc et al. (2017), defined on
124 a spherical grid centered on Ganymede with the same radial range but
125 with different θ and ϕ distributions compared to the ionospheric grid.
126 The neutral species n considered are O_2 , H_2O , H_2 , H , O , OH .

127 The ionosphere is created from ionization of the neutral exosphere. During
128 a given simulation, one ion species i (O_2^+ , OH^+ , H^+ , H_2^+ , H_2O^+ and O^+) is
129 produced. The test particles representing ion i are created at random posi-
130 tions in every cell of the exospheric grid where they get assigned a weight and
131 an initial velocity. The weight, W_j , equals the number of physical particles
132 represented by the test particle, and is assigned according to the following
133 formula:

$$W_j = dt \times V_{cell,exo} \times \sum_n n_n \times \nu_{i,n} \quad (1)$$

134 where dt is the timestep, $V_{cell,exo}$ is the volume of the cell of the exospheric
 135 grid, n_n is the number density of the neutral species n in the cell where the
 136 macro-particle is produced and $\nu_{i,n}$ is the ionization frequency of the ion
 137 species i generated from the ionization of the neutral n (see Section 3.1).

138 The initial velocity of the test particle, $\vec{v}_j(t = 0)$, is assigned in relation
 139 to the average velocity \vec{v}_n of the neutral species in the cell where the particle
 140 is produced, according to the following equation:

$$\vec{v}_j(t = 0) = \frac{\sum_n n_n \times \nu_{j,n} \times \left(\vec{v}_n \pm R \sqrt{2k_B T_n / m_j} \right)}{\sum_n n_n \times \nu_{j,n}} \quad (2)$$

141 where the sum is over all neutral species n whose ionization can lead to
 142 the ion species i , T_n is the temperature of the neutral species n and R is a
 143 uniformly distributed random number between 0 and 1 that generates the
 144 velocity dispersion for the ionospheric species. Although this is an average of
 145 the range of possible ion velocities, it turns out that the exact value of this
 146 parameter is irrelevant since the ions are quickly accelerated by the ambient
 147 electric and magnetic fields to speeds which are significantly higher compared
 148 to the speeds of the neutral species. A test simulation was performed, where
 149 a null velocity was assigned to the test particles, and the effect on the results
 150 was negligible.

151 The newborn test particle j is thus subject to the Lorentz force (gravity
 152 was verified to have a negligible effect on the motion), yielding:

$$m_j \frac{d\vec{v}_j}{dt} = q_j(\vec{E} + \vec{v}_j \times \vec{B}) \quad (3)$$

153 where \vec{E} and \vec{B} are the electric and magnetic fields, respectively, m_j is the
 154 ion's mass and q_j the electric charge of the test particle. We tested different
 155 algorithms with an adaptive timestep to integrate Equation 3, including Eu-
 156 ler, RK4 and Boris (Boris (1970)). The results did not change significantly
 157 between different algorithms, so we opted for the Boris scheme owing to its
 158 lower computational cost. We are aware that Skeel and Gear (1992) warned
 159 that Verlet-like algorithms - which Boris belongs to - can be unstable if used
 160 with an adaptive timestep. However, we applied this scheme to the field envi-
 161 ronment around Ganymede and found no noticeable difference in the results
 162 compared with a simulation that used the same algorithm but with a fixed
 163 timestep. Due to the significantly reduced computation time involved in a
 164 simulation with adaptive timestep, we chose to stick with this method. At
 165 each iteration the timestep is calculated to meet the following criteria:

- 166 • The distance travelled by the test particle must not exceed the size of
 167 the surrounding ionospheric grid cells, such that cells are not skipped
 168 from one timestep to the next (also known as 'CFL condition');
- 169 • The distance travelled by the test particle must not exceed the reso-
 170 lution of the hybrid grid, such that particles feel the correct Lorentz
 171 force down to the resolution of the hybrid grid;
- 172 • The test particle must not travel more than $1/20^{\text{th}}$ of the instant gyro-
 173 radius in order to simulate a sufficiently realistic path.

174 The test particles are followed until either they impact the moon’s sur-
 175 face or they cross the outer boundaries of the simulation grid. Throughout
 176 the trajectory, the weight and the velocity of the test particle are saved in
 177 each cell that the particle traversed. At the end of the simulation, when
 178 all test particle trajectories have been simulated, the number density $n_{i,cell}$,
 179 bulk velocity $\vec{u}_{i,cell}$, and temperature $T_{i,cell}$ of the ion species simulated are
 180 calculated for each cell according to the following equations:

$$n_{i,cell} = \frac{\sum_j W_j}{V_{cell,iono} \times N_{stat}}, \quad (4)$$

$$\vec{u}_{i,cell} = \frac{\sum_j \vec{v}_j \times W_j}{\sum_j W_j}, \quad (5)$$

$$T_{i,cell} = \frac{m_i}{3k_B} \left(\frac{\sum_j |\vec{v}_j|^2 \times W_j}{\sum_j W_j} - |\vec{u}_{i,cell}|^2 \right) \quad (6)$$

181 where $V_{cell,iono}$ is the volume of the ionospheric grid cell, N_{stat} is a sta-
 182 tistical parameter representing the number of test particles injected initially
 183 per exospheric grid cell, k_B is the Boltzmann’s constant, and W_j and \vec{v}_j are
 184 the weight and velocity, respectively, of the test particles deposited at each
 185 iteration in the cell. The sums run over all iterations and test particles. 3D
 186 maps of these quantities are generated separately for each ion species.

187 The simulation records also the individual test particle trajectories, al-
 188 lowing an easier physical interpretation of the 3D maps.

189 3. Simulation inputs and model assumptions

190 We present here the inputs for the simulations. These include: the sources
 191 for the ionization processes (Section 3.1) the configuration of the exosphere

Jupiter’s local time	10 AM
Solar flux activity	minimum
Jupiter heliocentric distance	5.46 AU
Location of Ganymede with respect to the plasma sheet	Above
Background magnetic field (nT)	(0,-79,-79)

Table 1: Simulation conditions assumed in our model which are based on the Galileo G2 flyby.

192 from the model of Leblanc et al. (2017) (Section 3.2) and the configuration
193 of the magnetosphere (Section 3.3). The model assumptions are described in
194 Section 3.4. For the maps in Sections 3 and 4 we use the GPhiO coordinate
195 system, centered on Ganymede, in which the X-axis points to the direction
196 of corotation of the Jovian plasma (which is also the direction of Ganymede’s
197 orbital motion), the Y-axis points towards Jupiter and the Z-axis completes
198 the right-handed coordinate system. For the simulations we chose, to repro-
199 duce Ganymede’s environment during the G2 flyby to compare our results
200 with observations (see Section 5). Table 1 provides a list of the conditions
201 that were assumed.

202 3.1. Ionization sources

203 3.1.1. Photo-ionization

204 Ganymede’s sunlit exosphere is constantly photo-ionized by solar EUV
205 radiation. The photo-ionization frequency of the ion species i , ν_i^γ , is calcu-
206 lated as follows:

$$\nu_i^\gamma = \sum_n \int_0^{\lambda_{th}} d\lambda I^\infty(\lambda) \times \sigma_{i,n}^{ion}(\lambda) \quad (7)$$

207 where λ is the radiation wavelength, λ_{th} is the threshold wavelength for
 208 ionization, $\sigma_{i,n}^{ion}(\lambda)$ is the ionization cross-section of the neutral n , producing
 209 the ion species i , $I^\infty(\lambda)$ is the unattenuated solar radiation spectral flux at
 210 Ganymede's orbit and the sum runs over all neutral species which produce i .

211 The solar activity was close to its minimum at the time of the G2 flyby (see
 212 Table 1), hence we used a corresponding solar flux. The data for the solar ra-
 213 diation flux was obtained from the TIMED/SEE database (<http://lasp.colorado.edu/see/>,
 214 Woods et al. (2005)) at 1 AU and extrapolated to Jupiter's orbital distance
 215 at 5.46 AU.

216 Table 2 provides the list of ionization processes considered in our model,
 217 along with the reference for ionization cross-sections and associated ioniza-
 218 tion frequencies. The photo-ionization frequencies were compared to those
 219 reported by Huebner and Mukherjee (2015) at low solar activity, and were
 220 found to be in good agreement (within 10%).

221 3.1.2. *Electron impact*

222 The Jovian plasma is able to partially penetrate inside Ganymede's mag-
 223 netosphere, and the energetic electrons ($>$ tens of eV) are able to ionize the
 224 neutral exosphere. Unfortunately, no data is available for the combined spa-
 225 tial and energetic distribution of electrons inside the magnetosphere. We
 226 would expect an asymmetry in the energy distribution between the open and
 227 closed magnetic field line regions. In particular, in the region of closed mag-
 228 netic field lines we would expect mainly low energy electrons to be present

Table 2: List of ionization reactions, the respective ionization frequencies, considered in the ionospheric model and calculated with the cross-sections referenced in the 3rd column. Electron-impact processes, frequency values and references are given in parenthesis. The photo-ionization frequencies were calculated at solar minimum conditions and given at the location of Jupiter (see Section 3.1).

Ionization by solar photons (electrons)	$\nu^{h\nu}$ (ν^e) [10^{-8} s^{-1}]	Ref.
$H + h\nu (e^-) \rightarrow H^+ + e^- (+ e^-)$	0.24 (2.41)	1
$H_2 + h\nu (e^-) \rightarrow H_2^+ + e^- (+ e^-)$	0.23 (3.02)	2
$H_2 + h\nu (e^-) \rightarrow H + H^+ + e^- (+ e^-)$	0.01 (0.24)	2
$H_2O + h\nu (e^-) \rightarrow H_2O^+ + e^- (+ e^-)$	1.13 (4.25)	3
$H_2O + h\nu (e^-) \rightarrow H + OH^+ + e^- (+ e^-)$	0.23 (1.29)	3
$H_2O + h\nu (e^-) \rightarrow O^+ + H_2 + e^- (+ e^-)$	0.02 (0.19)	3
$H_2O + h\nu (e^-) \rightarrow H^+ + OH + e^- (+ e^-)$	0.11 (1.03)	3
$O + h\nu (e^-) \rightarrow O^+ + e^- (+ e^-)$	0.87 (4.90)	4
$O_2 + h\nu (e^-) \rightarrow O_2^+ + e^- (+ e^-)$	1.75 (9.05)	5
$O_2 + h\nu (e^-) \rightarrow O + O^+ + e^- (+ e^-)$	0.44 (0.90)	5
$OH + h\nu (e^-) \rightarrow OH^+ + e^- (+ e^-)$	1.75 (5.76)	6

¹ Verner et al. (1996) (Galand et al. (2009))

² Galand et al. (2009) (Galand et al. (2009))

³ Vignen and Galand (2013) (Itikawa and Mason (2005))

⁴ Cui et al. (2011) (Laher and Gilmore (1990))

⁵ 0-1.5 nm: Branching ratio of Stolte et al. (1998) applied to the photo-absorption cross-section from Avakyan (1998); 1.5-12 nm: Stolte et al. (1998); 12-50 nm: Brion et al. (1979); above 50 nm: Schunk and Nagy (2004). (Straub et al. (1996))

⁶ Photo-ionization rate of OH was set equal to that of H₂O, after Schreier et al. (1993) (Joshiyura et al. (2001))

229 from photo-ionization of the neutral atmosphere, and not energetic electrons
 230 from the Jovian plasma sheet which are not able to penetrate (Williams
 231 et al. (1998)). Due to our limited knowledge of the electron population in-
 232 side Ganymede’s magnetosphere, ionization from Jovian electrons is assumed
 233 to take place only within the region of open magnetic field lines. The energy
 234 distribution of the Jovian electrons is set to be spatially constant within this
 235 simulation volume. The ionization frequency, ν_i^e , is calculated as follows:

$$\nu_i^e = \sum_n \int_{E_{th}}^{E_{max}} dE I(E) \sigma_{e,n}^{ion}(E) \quad (8)$$

236 where E is the electron energy, E_{th} is the energy threshold for electron-
 237 impact ionization, E_{max} is the highest electron energy available from data,
 238 $I(E)$ is the electron differential flux and $\sigma_{e,n}^{ion}(E)$ is the energy-dependent ion-
 239 ization cross-section for the electron impact on the neutral species n produc-
 240 ing the ion i . The sum runs over all neutral species n whose electron-impact
 241 ionization can lead to i .

242 Our approach differs from that of Marconi (2007) and Turc et al. (2014),
 243 who assumed a constant electron number density of 70 cm^{-3} (only in the polar
 244 region in the model of Turc et al. (2014)) and temperature of 20 eV in relation
 245 to exospheric loss processes. The value for the number density corresponds
 246 to the average between measurements taken during the G1 and G2 flybys
 247 and extrapolated to $0.2 R_G$, while the electron temperature corresponds to
 248 that measured at Europa. By taking the moments of the black, dashed
 249 distribution in Figure 1 (integrating from 14 eV to 5.16 keV), one obtains
 250 a density of 0.76 cm^{-3} and a temperature of around 140 eV. The density is
 251 significantly lower compared to that used in the exospheric models, which

252 instead relied on measurements that captured the full electron population,
253 i.e., including electrons with energies below 14 eV. As a result, the electron-
254 impact ionisation frequencies obtained with our approach are lower by more
255 than one order of magnitude.

256 Furthermore, based on the differential cross-section relation from Opal
257 et al. (1971) for electron-impact ionization, most of the secondary electrons
258 produced were found to have energies which are either lower than the ioniza-
259 tion threshold of the neutral species or low enough to be in the part of the
260 energy spectrum where the ionization cross-section is low. As a result, most
261 of the secondary electrons would not be able to efficiently ionize: we have
262 neglected their contribution in the model.

263 To simulate the ionization from electron impact we combined the electron
264 energy distributions outside Ganymede's magnetosphere and away from the
265 plasma sheet from Scudder et al. (1981) and Paranicas et al. (1999), as shown
266 in Figure 1. We also verified that the electron flux presented by Cooper et al.
267 (2001) (who used data from the Galileo EPD instrument) and Paranicas et al.
268 (1999) (who used data from both the Galileo PLS and EPD instruments) are
269 consistent between each other, as both presented data for the G2 flyby.

270 The ionization frequencies calculated for electron-impact are given in Ta-
271 ble 2. We found for all neutral-ion pair considered that electron-impact ion-
272 ization dominates over photo-ionization in the region of open magnetic field
273 lines, where both ionizing sources are active (electron impact is not included
274 in the region of closed magnetic field lines).

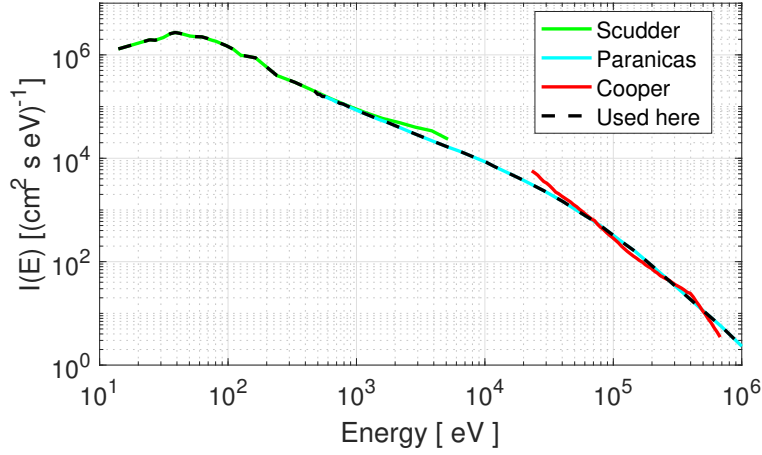


Figure 1: Electron differential flux as a function of energy, outside the Jovian plasma sheet near Ganymede. Isotropy was assumed. The green curve shows the flux computed from the distribution function in Scudder et al. (1981) adapted to Ganymede’s orbital distance, the cyan curve shows the flux presented in Paranicas et al. (1999), the red curve shows the flux presented in Cooper et al. (2001) and the dashed black curve shows the combined flux adopted in our simulation.

275 3.2. Exosphere

276 The exospheric model of Leblanc et al. (2017) simulates the dynamical
 277 variation of the exosphere as Ganymede revolves around Jupiter. This affects
 278 the ionosphere because the spatial distribution of the neutral species changes
 279 in Ganymede’s reference frame along with the location of the illuminated
 280 region.

281 Figure 2 shows in the XZ plane the number density maps of the three
 282 major neutral species, O₂, H₂ and H₂O, from the exospheric model of Leblanc
 283 et al. (2017). O₂ is dominant close to the surface, followed by H₂, since these
 284 are the only species that do not stick to the surface. At higher altitudes, the

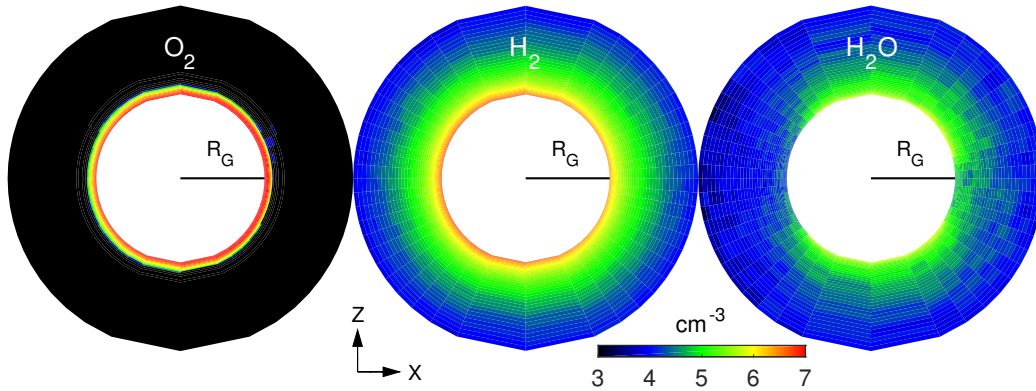


Figure 2: Number density profile of the major neutral species in the XZ plane, from the exospheric model of Leblanc et al. (2017) when Ganymede is at 10 AM in Jupiter’s local time.

285 exosphere is dominated by H_2 and H_2O . There is an asymmetry between the
 286 dawn and dusk sectors, with the dusk sector achieving the highest densities
 287 (not shown). O_2 and H_2 , by not sticking to the surface, can accumulate
 288 near the surface. They are primarily produced on the day side (sputtering
 289 being surface-temperature dependent), where they bounce on the surface,
 290 and destroyed in the night side where their residency time is larger due to a
 291 lower surface temperature. Destruction on the night side occurs in the region
 292 of open magnetic field lines where electron-impact ionisation and dissociation
 293 are turned on. Leblanc et al. (2017) also showed that O_2 molecules move very
 294 slowly in Ganymede’s frame (with respect to ionization lifetime) so that they
 295 accumulate on the day side, leading to a peak of density at dusk. It is less
 296 true for H_2 because its motion in Ganymede’s frame is much faster.

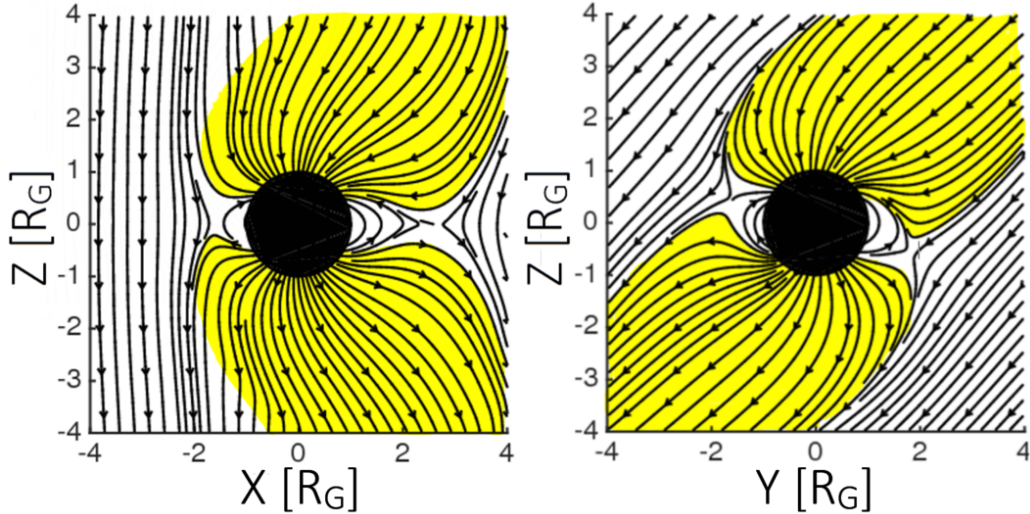


Figure 3: Magnetic field configuration around Ganymede above the plasma sheet from the hybrid model of Leclercq et al. (2016). 1 RG \equiv 1 Ganymede’s radius \equiv 2634 km. The yellow region represents the cut of the Alfvén wings in each plane.

297 3.3. Magnetosphere configuration

298 To simulate Ganymede’s magnetosphere we used the hybrid model of
 299 Leclercq et al. (2016) applied to Ganymede under G2 conditions, which are
 300 listed in Table 1. We checked that the lifetime of ionospheric species in the
 301 simulation is typically a few minutes. In this time frame the magnetosphere
 302 does not change significantly, so it is safe to assume a constant configuration
 303 of the electric and magnetic fields throughout the simulation.

304 Figure 3 shows a portion of the magnetic field topology used as input to
 305 the ionospheric model. The yellow regions correspond to the section of the
 306 Alfvén wings that intersect each plane. The magnetic field lines are bent by
 307 45° with respect to the Z-axis and point away from Jupiter as Ganymede is
 308 above the plasma sheet.

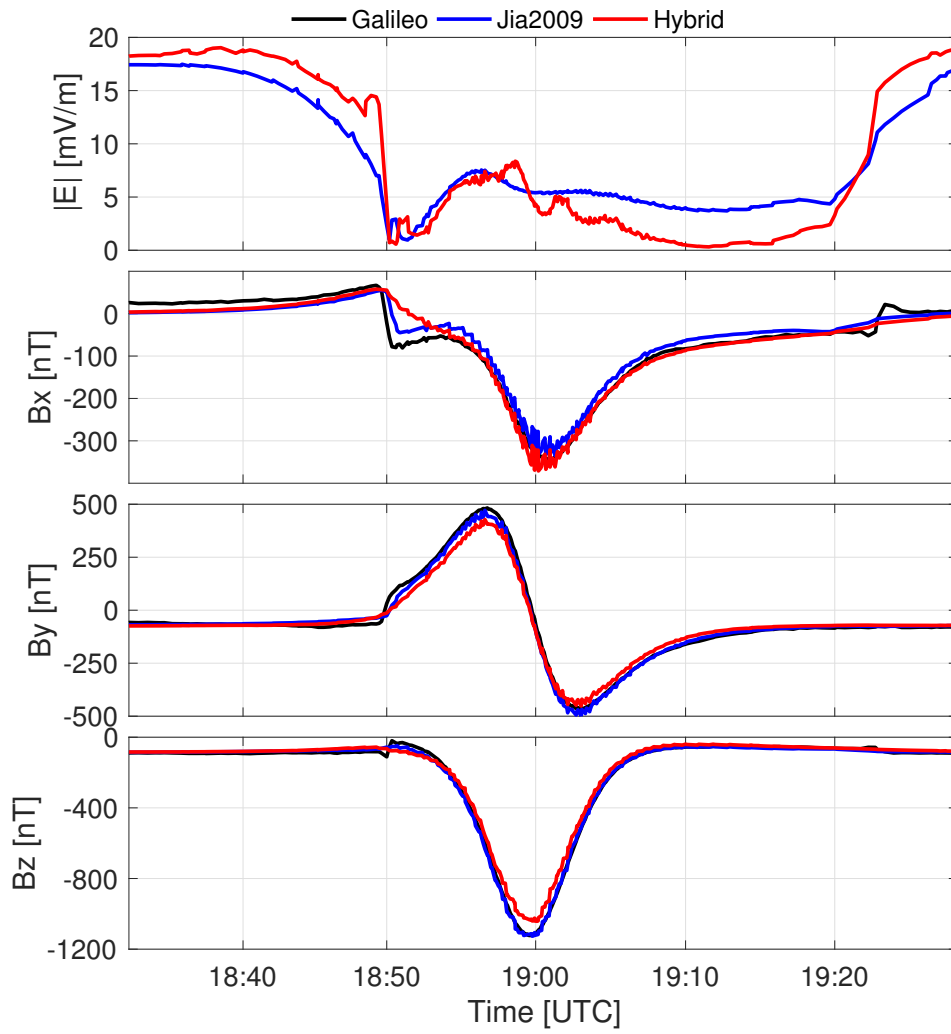


Figure 4: Comparison of the simulated electric field magnitude (top panel) and magnetic field components (bottom panels) along the G2 trajectory between the hybrid simulation of Leclercq et al. (2016) (red curve) and the MHD simulation of Jia et al. (2009) (blue curve). For the magnetic field components, the observed values are shown by the black curve.

309 To study how the results from the test particle model are influenced by
310 the input fields, we have also run simulations using the fields from the MHD
311 model of Ganymede’s magnetosphere developed by Jia et al. (2009). This
312 model makes some different assumptions compared to the hybrid model, in-
313 cluding the plasma composition and the boundary conditions at the iono-
314 spheric layer and upstream injection plane. The hybrid model of Leclercq
315 et al. (2016) simulated two Jovian plasma species with different fractional
316 compositions: O^+ (87%) and H^+ (13%). The plasma density at the up-
317 stream injection plane was set to 4 cm^{-3} to match the Jovian plasma sheet
318 electron density reported by Gurnett et al. (1996), and the ionosphere was
319 prescribed a number density at the surface of 500 cm^{-3} with an exponential
320 decay governed by a scale height of 125 km. The ionosphere was assumed to
321 be composed of O^+ only, with a spherically symmetric configuration. In the
322 MHD model of Jia et al. (2009) the Jovian plasma was simulated as a single
323 fluid with density of 28 AMU/cm^3 , which corresponds to less than 2 cm^{-3} if
324 O^+ is assumed. For the ionospheric boundary layer, their model assumed a
325 density of 550 AMU/cm^3 , which corresponds to a number density of around
326 34 cm^{-3} if O^+ is assumed. The different choices for the input conditions
327 lead to some differences in the field configurations, in particular close to the
328 surface (later discussed in Section 5).

329 The top panel of Figure 4 shows the magnitude of the electric field along
330 the G2 trajectory as found by the hybrid and MHD models. The other three
331 panels of Figure 4 show the comparison of the Cartesian components of the
332 magnetic field with Galileo measurements. Overall, the magnetic field sim-
333 ulated by both models features a close correspondence with the observed

334 values for all three \mathbf{B} field components. Between the two models, the MHD
 335 simulation finds a better agreement with observations. For the hybrid model,
 336 departures from observations occur near the magnetopause boundary cross-
 337 ings at 18:50 UTC and 19:22 UTC for the x-component, and a slight shift
 338 between data and simulated values is seen near closest approach at 19:00
 339 UTC for the y- and z- components. Further comparison between the two
 340 models are highlighted in Section 5.

341 *3.4. Model assumptions*

342 *3.4.1. Optically thin approximation*

343 In dense atmospheres the solar radiation gets absorbed by the neutral gas.
 344 The initially unattenuated spectral flux decreases as the radiation penetrates
 345 deeper in the atmosphere, according to the Beer-Lambert law:

$$I(\vec{r}, \lambda) = I^\infty(\lambda) \times e^{-\tau(\vec{r}, \lambda)} \quad (9)$$

346 where $I^\infty(\lambda)$ is the unattenuated solar spectral flux, λ , the radiation wave-
 347 length, \vec{r} , the position vector and τ is the optical depth which parametrizes
 348 the absorption factor. It is defined as:

$$\tau(\vec{r}, \lambda) = \sum_n \sigma_n^{abs}(\lambda) \int_{s(\vec{r})}^{\infty} ds' n_n(s') \quad (10)$$

349 where σ_n^{abs} is the photo-absorption cross-section for the neutral species
 350 n and $n_n(\vec{r})$ its number density. The integral is over the line of sight -
 351 associated with abscissa s' - from s at position \vec{r} to the solar direction and
 352 the sum includes all neutral species present along the line of sight. If τ is
 353 close to 0 at a given position and wavelength then the solar radiation is

354 unattenuated: the atmosphere is optically thin for that wavelength at that
355 position.

356 From the number density maps obtained from the exospheric model of
357 Leblanc et al. (2017) we calculated τ for Ganymede’s exosphere. Figure 5c
358 shows the absorption cross-sections that were used to calculate the optical
359 depth for O₂, H₂ and H₂O, the major species present in Ganymede’s neutral
360 atmosphere. In terms of number density, O₂ dominates below 160 km, while
361 H₂ and H₂O dominate above that. For O₂, the absorption cross-section
362 peaks at 63 nm, while for H₂ the peak is at 98 nm, as seen in Figure 5c. The
363 relative abundance of these two species leads to a peak of approximately 0.03
364 in the optical depth at 63 nm (see Figure 5a) in the polar region (see Figure
365 5b). A maximum optical depth of 0.03 implies that even at the surface the
366 solar intensity is not significantly attenuated. This result applies over the
367 full longitude range. Therefore, it is justified to assume the exosphere to
368 be optically thin: the solar radiation intensity is the same everywhere in the
369 simulation volume, except in the night side where it is absent. This translates
370 into a spatially constant photo-ionization frequency over the sunlit region of
371 the simulation domain, which we have assumed in our model.

372 3.4.2. *Collisional and chemical properties of the ionosphere*

373 The ionospheric species can undergo chemical reactions and collisions
374 with the atmospheric neutral species. To assess how important these pro-
375 cesses are for each ion species in each cell of the simulation grid, the ion’s
376 chemical lifetime was compared with its transport timescale. The chemical
377 lifetime of an ion species i is given by:

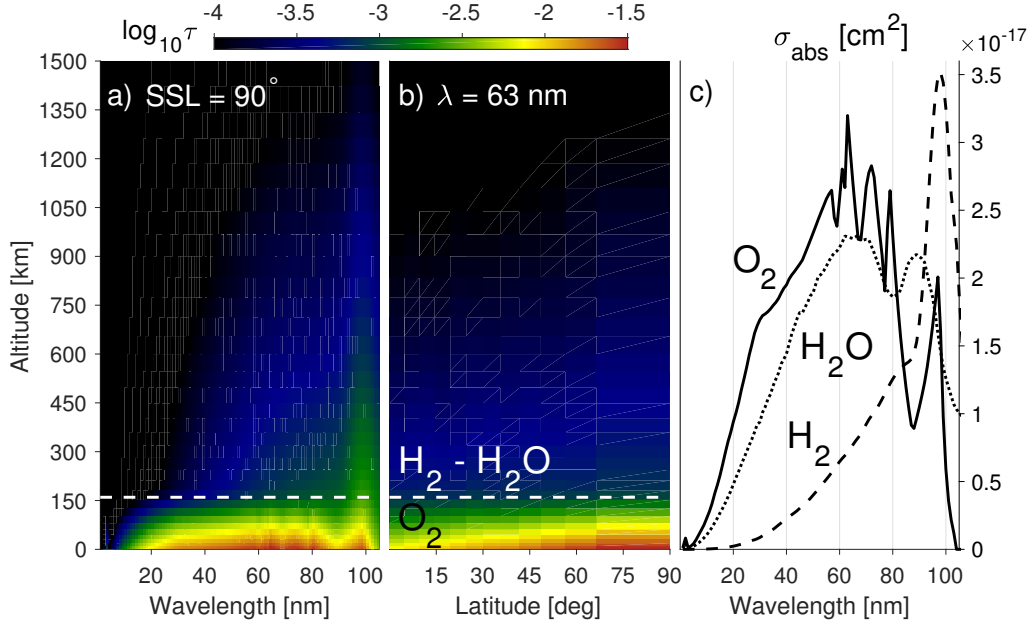


Figure 5: a) Optical depth at the North pole as a function of altitude (y-axis) and wavelength (x-axis). b) Optical depth at the subsolar longitude as a function of altitude (y-axis) and latitude (x-axis) for $\lambda = 63$ nm. 0° corresponds to the equator and 90° to the North pole. c) Absorption cross-section as a function of wavelength for O_2 , H_2 and H_2O . References for O_2 cross-section values: 0-1.5 nm: Branching ratio of Stolte et al. (1998) applied to the photo-absorption cross-section from Avakyan (1998); 1.5-12 nm: Stolte et al. (1998); 12-50 nm: Brion et al. (1979); above 50 nm: Schunk and Nagy (2004). Reference for H_2 cross-section values: Backx et al. (1976). Reference for H_2O cross-section values: Vigren and Galand (2013).

$$\tau_{i,k}^{chem} = \frac{1}{\alpha_{i,k} n_k} \quad (11)$$

378 where $\alpha_{i,k}$ is the coefficient rate of the chemical reaction considered be-
 379 tween the ion species i and atmospheric species k , in $\text{cm}^3 \text{s}^{-1}$, and n_k is the
 380 number density of k , in cm^{-3} . The species k can be exospheric (ion-neutral

381 reaction) or an electron (ion-electron dissociative recombination). This cal-
 382 culation was done for all major chemical reactions between the ionospheric
 383 ions and the exospheric species or electrons. Reactions involving charge-
 384 exchange were also considered, as simple momentum transfer collisions are
 385 inefficient for typical energies of Ganymede’s ionospheric ions, above 0.1eV
 386 (Banks (1966)). To calculate the transport timescale in each cell we com-
 387 puted the time taken by the ion to travel a distance equal to the local ion
 388 scale height H_i , i.e.:

$$\tau_i^{tran} = \frac{H_i}{u_{i,cell}} \quad (12)$$

389 where $u_{i,cell}$ is the ion bulk velocity derived from a simulation assuming a
 390 collisionless ionosphere and $H_i = n_i/|(dn_i/dr)|$ where n_i is the ion number
 391 density.

392 Figure 6 shows a comparison between the timescales for transport and
 393 reactions with the neutral species for the case of O^+ and O_2^+ , the major
 394 constituents of the ionosphere (see Section 4). The calculation was carried
 395 out in three distinct regions: the northern polar region, the equatorial region
 396 and the southern polar region. These are separated by the open-close field
 397 line boundaries (OCFLB) at mid-latitudes, shown as solid, black lines in the
 398 top panels of Figure 6. The ion scale height and velocity were taken from a
 399 run of our model which assumed no interaction with the neutral exosphere,
 400 and the exospheric densities were taken from the model of Leblanc et al.
 401 (2017) (the modeled exosphere used was the “low sublimation” case, in which
 402 no semi-dense H_2O atmosphere forms in the subsolar region, see Section 2.3
 403 in Leblanc et al. (2017)). For each region and each altitude, the plotted

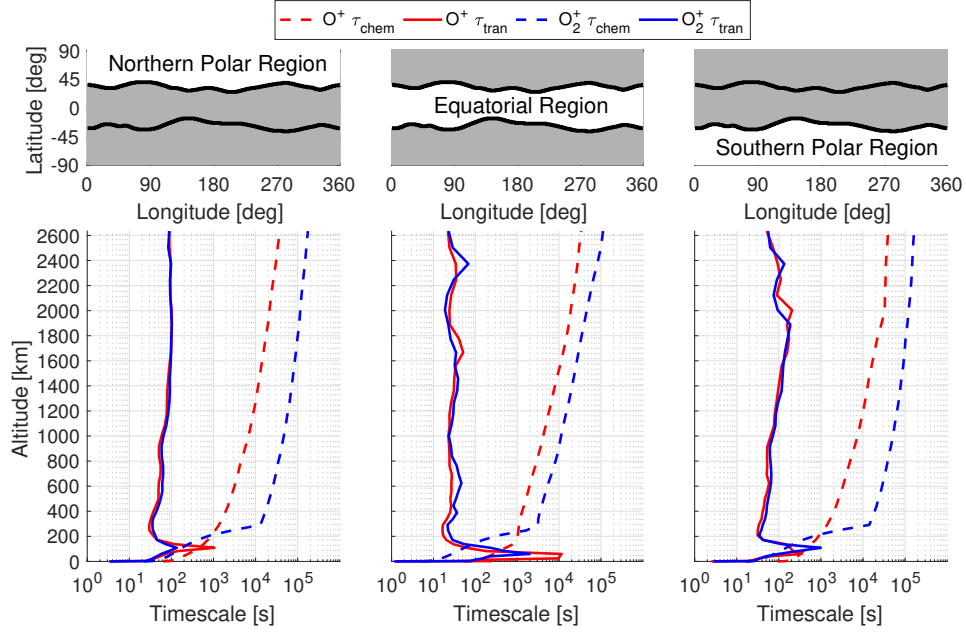


Figure 6: Top: Maps indicating the latitude-longitude domain of calculation considered for the plots in each respective bottom panel. The regions are separated by the open-close magnetic field line boundaries, plotted as solid, black lines. The white area corresponds to the domain of calculation, while the grey area shows the excluded regions. Bottom: Plots of the chemical (τ_{chem}) and transport (τ_{tran}) timescales of O^+ (red) and O_2^+ (blue) as functions of altitude. For each region and each altitude, the plotted value corresponds to the average over all longitudes and latitudes within the calculation domain, shown by the white area on the top panel. Solid lines correspond to transport timescales, and dashed lines correspond to chemical timescales, corresponding to charge exchange (as timescales associated with ion-neutral collisions are larger).

404 value is the average over all longitudes and latitudes within that region (the
405 white area in the top panels of Figure 6). This is justified as the ionospheric
406 parameters, such as density and velocity, in that altitude range (0 to 2600
407 km) differ primarily between regions and not longitude (see Section 4.2.1)
408 due to the configuration of the electromagnetic field (see Section 3.3).

409 The profiles for the chemical timescale are found to increase for both ions
410 as a function of altitude in all regions, in concomitance with the decreasing
411 density of exospheric species. Below 200 km, this timescale is driven by the
412 charge-exchange reaction with O_2 , while at higher altitudes it is driven by
413 charge-exchange with H_2 , the locally dominant species (see Figure 2). The
414 profiles for the transport timescale are similar in the northern and southern
415 polar regions. A peak is seen at approximately 100 km, of the order of 10^2
416 to 10^3 s. At higher altitudes, the average timescale reaches a stable value
417 of about 100 s for both species. In the equatorial region, the peak occurs
418 approximately at the same altitude as in the polar regions, but the value is
419 at least one order of magnitude higher for both species. At higher altitudes
420 the average is more or less stable between 10 and 100 s. In all regions, the
421 peak at low altitudes originates from a local spike in the ion scale height,
422 corresponding to a plateau in the density profile close to the surface (not
423 shown). At high altitudes, the average transport timescale is lower in the
424 equatorial region as the ions inside the closed field lines move at higher speeds.

425 For both ions, the chemical lifetime is significantly greater than the trans-
426 port timescale except very close to the surface (below approximately 200 km),
427 where the number density of O_2 is the largest: there, the two are comparable,
428 as shown in the bottom panels of Figure 6. As a result, very close to the

429 surface charge-exchange processes with O_2 may be significant. However, by
430 comparing the production rate of O_2^+ from this reaction to that from other
431 ionization sources of O_2 (photoionization and electron impact), we found
432 that the charge-exchange reaction contributes at most to 1% of the total
433 local production rate, hence is a negligible source. We still included the
434 charge-exchange reaction between O_2 and O_2^+/O^+ in our model, and checked
435 that this addition, slowing down O_2^+ , has almost no effect on the density map
436 of either ion species.

437 H_2O^+ was found to react with its neutral parent close to the surface, where
438 densities are highest. The chemical reaction is $H_2O + H_2O^+ \rightarrow H_3O^+ + OH$,
439 hence H_2O^+ is converted to H_3O^+ . However, the latter species was found
440 to be lost mainly through transport, contrarily to what had been assumed
441 by Eviatar et al. (2001), since the chemical loss timescale of recombination
442 with electrons was found to exceed by 3-4 orders of magnitude the trans-
443 port timescale. As H_2O^+ and H_3O^+ have similar masses, it does not matter
444 which species is simulated, and for this reason we considered H_2O^+ to be
445 collisionless, considering it effectively like a “water ion”.

446 The other ionospheric species are minor components in the ionosphere and
447 their chemical timescale was found to vastly exceed the transport timescale
448 everywhere. In particular, H_2^+ is primarily lost by transport, and its recom-
449 bination with electrons is negligible everywhere unlike what Cessateur et al.
450 (2012) assumed. Based on our analysis, it is therefore justified to assume all
451 ionospheric species to not undergo any collision or chemical reaction.

452 3.4.3. *No secondary electrons*

453 As shown in Section 3.4.1, the atmosphere is optically thin, so the photo-
454 ionization process is dominated by the lower end of the EUV energy spec-
455 trum everywhere in Ganymede’s exosphere. The mean energy of the photo-
456 electrons produced is between 6 eV for H₂, 22 eV for O and values in between
457 for H₂O and O₂ at solar minimum conditions (Huebner et al. (1992)). These
458 values are close or below the ionization threshold. Combined by the fact
459 that electron-impact ionization cross-sections are very low below a few tens
460 of eV, the contribution of photo-electrons to the ionization of the exosphere
461 is negligible compared with photo-ionization and has been neglected here.

462 4. Results

463 4.1. *Overview*

464 Table 3 shows a comparison of the total production, impact and escape
465 rates between the ion species simulated. The total production rate is dom-
466 inated by O₂⁺ as a direct consequence of O₂ dominating in the neutral ex-
467 osphere. For each ion species, the main production channel is ionization of
468 the parent neutral, except for O⁺, which is primarily produced via dissocia-
469 tive ionization of O₂. For H₂⁺, H₂O⁺, H⁺ and OH⁺, the majority of ions
470 produced escape from the simulation box, while for O⁺ and O₂⁺ more than
471 half of the ions produced]impacts Ganymede’s surface. This difference is
472 due to the spatial distribution of O₂ in the exosphere: being concentrated
473 mostly close to the surface (see left panel, Figure 2) the oxygen ions, being
474 also created close to the surface, have a better chance of impact compared
475 to, for example, H₂O⁺ produced from H₂O which is more spread in altitude

476 (see right panel, Figure 2).

Rate ($\times 10^{23}\text{s}^{-1}$)	O_2^+	O^+	H_2^+	H_2O^+	H^+	OH^+
Total production	90.4	12.8	14.7	10.6	3.4	3.1
Impact	73.1	9.9	7.3	2.8	1.1	0.8
Escape	17.3	2.9	7.4	7.8	2.3	2.3
% of escape	19.1	22.7	50.3	73.6	67.6	74.2

Table 3: Comparison between ionospheric species in terms of total production, impact, and escape rates. The escape rate (third row) is derived from the difference between the total production (first row) and surface impact (second row) rates. The bottom line provides the percentage of escaping ions.

477 4.2. Number density, bulk velocity and temperature maps

478 We present 2D maps of the number density (Section 4.2.1), bulk veloc-
 479 ity (4.2.2) and temperature (Section 4.2.3) in three different planes for O_2^+ .
 480 Although the values of these quantities differ between ion species, the global
 481 structure of the maps and the main features highlighted are similar for all
 482 ions, hence only the results for O_2^+ are presented, owing to its dominance in
 483 terms of number density.

484 4.2.1. Number density

485 Panels a), b) and c) of Figure 7 show the number density of O_2^+ in the
 486 XZ, YZ and XY planes, respectively. The density profiles are not symmet-
 487 ric around the moon and reproduce the detailed structure of Ganymede's
 488 magnetosphere. From these plots we see that the ionospheric plasma is not

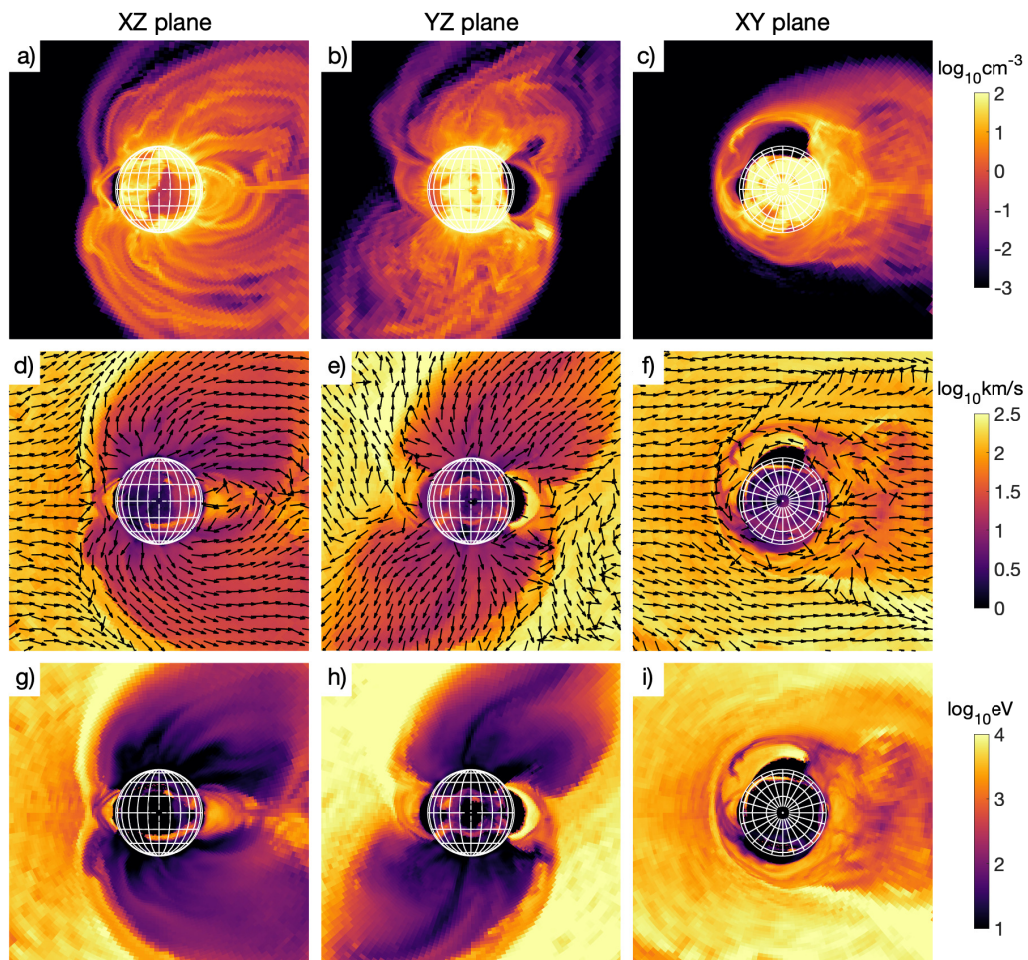


Figure 7: Maps of the distribution moments for O_2^+ with Ganymede at 11 a.m. in Jupiter's solar local time. All color scales are logarithmic. Top row: Number density. Middle row: Bulk velocity. Bottom row: Bulk temperature. For a generic plane "AB", 'A' points to the right and 'B' points up.

489 spatially confined close to the moon, but extends along the Alfvén wings and
490 in the direction of corotation of the Jovian plasma.

491 In the XZ and XY planes the Jovian plasma flows from the left to the right
492 of the plot, i.e. the upstream hemisphere is to the left of the moon. In this
493 region, the ionospheric plasma is confined within a distance of approximately
494 $1 R_G$ from the surface, corresponding to the location of the magnetopause in
495 the hybrid model (see Figure 3).

496 In all three planes we can distinguish three regions: the first with low
497 density (region I, black colour, $n_{O_2^+} < 10^{-3} \text{ cm}^{-3}$), the second with higher
498 density (region II, purple/ dark orange colour, $10^{-3} < n_{O_2^+} < 1 \text{ cm}^{-3}$) and a
499 region of relatively high density close to the moon (region III, orange/yellow
500 colour, $n_{O_2^+} > 1 \text{ cm}^{-3}$). In the XZ and YZ planes, the boundary between
501 regions I and II corresponds to the boundary of the Alfvén wings intersect-
502 ing each plane. Figure 3, showing the magnetic field lines considered in the
503 ionospheric simulation, helps to visualise the projection of the Alfvén wings
504 in these two planes. In the XZ and XY planes, region II extends also in
505 the positive X-direction. This is due to the ionospheric plasma leaving the
506 simulation box in the corotation direction and merging with the Jovian mag-
507 netospheric ions. Inside the Alfvén wings the plasma is denser because in this
508 region the electric field is weaker, hence the plasma moves slower compared
509 to outside (see Section 4.2.2). This results with ions accumulating inside the
510 wings.

511 Region III is found everywhere around the moon, close to the surface. In
512 the equatorial region, the high density extends up to the magnetopause in
513 the orbitally leading hemisphere, as seen in panels a) and c) of Figure 7. The

514 density in the equatorial region is enhanced by ions which are trapped inside
515 the closed field lines region and perform $\mathbf{E} \times \mathbf{B}$ drift motion around the moon
516 with typical energies of the keV order, hence forming partial radiation belts.
517 The energization of ionospheric ions occurs near the magnetopause boundary
518 in the equatorial region, where strong currents are present resulting from the
519 large curvature of the magnetic field lines. In the XZ and YZ planes, the
520 shape of the mirroring motion along closed magnetic field lines - as illustrated
521 in panels a) and b) - is recognised as the “rounded” curves, reproducing the
522 magnetic field lines, to the left and right of the moon.

523 There is an asymmetry in the ion density in the YZ plane in the equatorial
524 region between the +Y and -Y hemispheres (Figure 7b), with the number
525 density being significantly lower in the +Y hemisphere. This results from
526 Ganymede’s position with respect to the Sun. Since at the time of the G2
527 flyby the midday longitude (in GPhiO system) was 300° , and the midnight
528 longitude was 120° , the +Y region associated with closed magnetic field lines
529 near the equator is located in the moon’s shadow: no ionization of the neutral
530 exosphere occurs in the region of closed magnetic field lines. Therefore, no
531 plasma is generated in this region, resulting in a much reduced density, as
532 shown in Figure 7b.

533 Panels a) and b) of Figure 7 display some string-like features in the polar
534 regions. These are to be considered as noise in the electric field generated
535 by the hybrid model but which do not compromise the conclusions drawn
536 by our study. The fields were calculated with a resolution of 125 km close
537 to the moon and the noisy patterns suggest that in this region the resolu-
538 tion implemented by the hybrid model might be insufficient for Ganymede’s

539 magnetospheric environment or that in this region there is not enough par-
540 ticle statistics in the hybrid model. In Appendix Appendix A we compare
541 the maps in Figure 7 with those obtained using the MHD model to discern
542 features which are physical from those which are driven by the input fields.

543 *4.2.2. Bulk velocity*

544 Panels d), e) and f) of Figure 7 show the bulk velocity of O_2^+ in the XZ, YZ
545 and XY planes, respectively. As indicated by the arrows, the plasma flows in
546 the direction of corotation and escapes from the magnetosphere either in this
547 direction or through the Alfvén wings. On average, compared to the bulk
548 speed of the Jovian plasma sheet of 140 km/s found outside Ganymede’s
549 magnetosphere, the ionospheric plasma moves considerably slower inside
550 Ganymede’s magnetosphere and the Alfvén wings, while it moves faster at
551 the Alfvén wings boundaries. For O_2^+ , close to the moon the plasma moves
552 on average at 1-10 km/s, while near the wings’ boundaries the average speed
553 exceeds 1000 km/s. This difference arises mainly from the large difference
554 in the intensity of the electric field in these two regions. Inside the wings
555 the electric field is significantly weaker compared to that at its boundaries.
556 At the boundaries are found electric currents which, being associated to a
557 strong electric field, accelerate the ions. These currents run all the way along
558 the Jovian magnetic field lines linked to the Alfvén wings and close on one
559 end at Jupiter’s ionosphere (Kivelson et al. (2004)) and, on the other end, at
560 Ganymede’s magnetosphere.

561 *4.2.3. Temperature*

562 Panels g), h) and i) of Figure 7 show the temperature of O_2^+ in the XZ,
563 YZ and XY planes, respectively. Inside the Alfvén wings the average tem-
564 perature of O_2^+ (and also of the other simulated species, not shown here) is
565 of the order of 1 eV, but it increases rapidly at the wings’ boundaries and the
566 magnetopause regions on the upstream and downstream hemispheres. Note
567 the definition of temperature that is used here: it is related to the variance of
568 the velocity (see Equation 6). A low temperature corresponds to a popula-
569 tion of ions which statistically move at speeds close to the bulk speed, while
570 a large temperature indicates that the ions possess a wide range of speeds.
571 For the downstream magnetopause region (at a radial distance of approxi-
572 mately $2 R_G$ from the surface), the large temperature arises due to the strong
573 magnetopause currents. In this region, there co-exist ions which have been
574 accelerated by currents, hence moving fast, and locally newborn ions which
575 have just been produced and hence move slow. This causes a large variance
576 in the velocity which is reflected in the temperature parameter. A similar
577 argument applies to regions of Ganymede’s magnetosphere where electric
578 currents are present, namely the radiation belt (panels g), h) i)), the Alfvén
579 wing boundaries (panels g) and h)) and the upstream and downstream mag-
580 netopause regions (panels g) and i)). In these regions, ionospheric ions are
581 accelerated by \mathbf{E} and \mathbf{B} to energies greater than 1 keV.

582 **5. G2 flyby**

583 *5.1. Comparison between simulations and Galileo observations*

584 Located above the plasma sheet, the Galileo spacecraft did three flybys
585 of Ganymede: G1 in June 1996, G2 in September 1996 and G29 in December
586 2000. Unlike other flybys, G1, G2 and G28 were close enough to detect a
587 significant amount of ionospheric plasma according to our simulations. In
588 this section, we compare our simulations to observations from PLS and PWS
589 instruments during the G2 flyby. Closest approach to Ganymede occurred at
590 an altitude of 261 km above the moon’s surface in the northern polar region
591 (the closest amongst all flybys). We show results for simulations which were
592 driven by the electric and magnetic fields not only from the hybrid code of
593 Leclercq et al. (2016) (see Section 3.3) but also from the MHD model of Jia
594 et al. (2009). The goal is to check the robustness of our conclusions using
595 different magnetospheric models.

596 *5.1.1. Electron density*

597 Panel a) of Figure 8 shows the electron number density profile along the
598 G2 trajectory as measured by: the PWS instrument (Eviatar et al., 2001)
599 (black curve), an ionospheric simulation driven by fields from the hybrid
600 model of Leclercq et al. (2016) (red curve) and an ionospheric simulation,
601 driven by fields from the MHD model of Jia et al. (2009) (blue curve). The
602 electron number density was obtained by summing the ion density over all
603 ionospheric species, assuming plasma neutrality. The reader is referred to
604 Figure C.13 in Appendix C to visualize the volume mixing ratio of the iono-
605 spheric species along the spacecraft trajectory. The green curve shows the

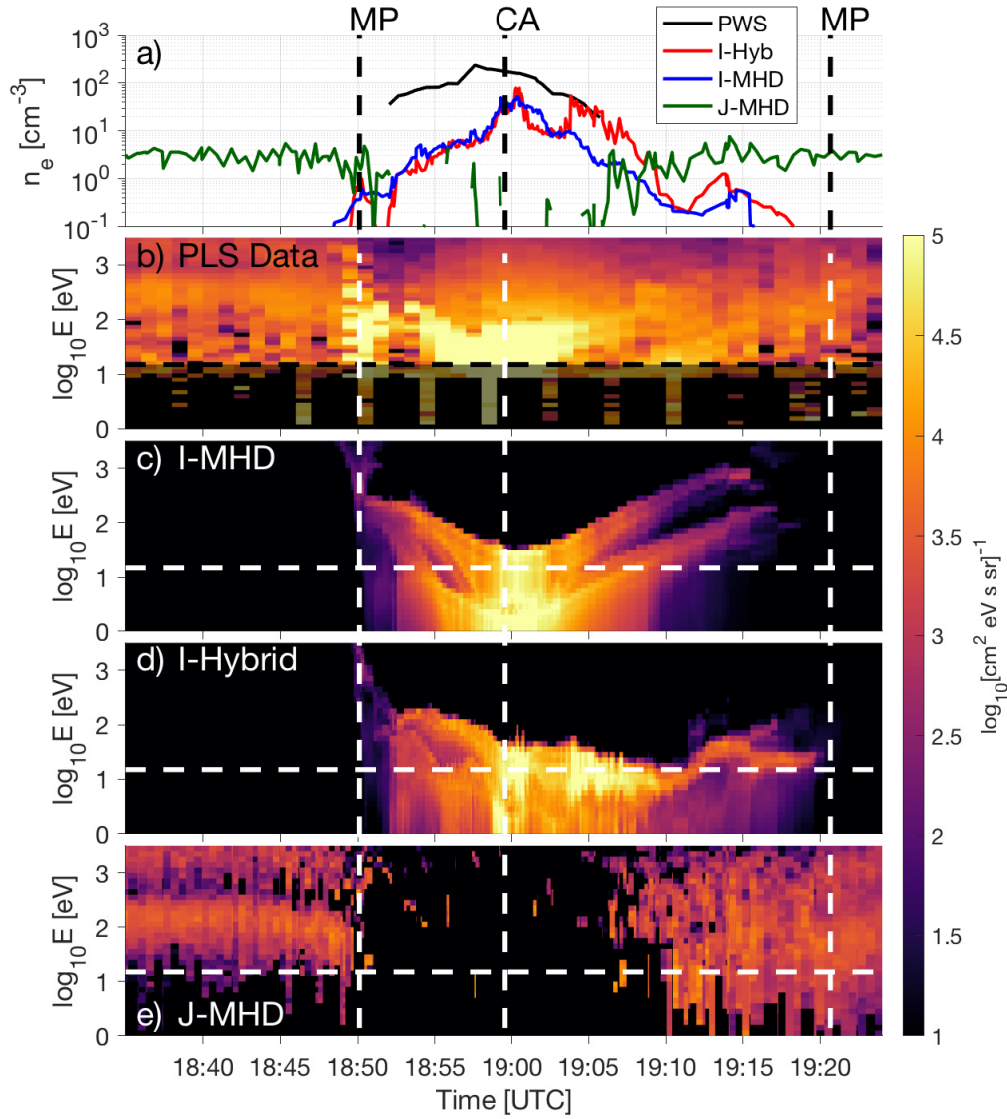


Figure 8: a): Electron density profiles along the G2 trajectory, from: the PWS instrument (black curve) (from Eviatar et al., 2001), the ionospheric simulation using the fields from the hybrid model of Leclercq et al. (2016) ('I-Hyb', red curve) and the ionospheric simulation using the fields from the MHD model of Jia et al. (2009) ('I-MHD', blue curve). The green curve shows the number density of Jovian thermal ions, simulated using the fields from the MHD model ('J-MHD'). b): Energy spectrogram of the total ion intensity (mean over angle) as recorded by the PLS instrument; below 15 eV (shaded region) the processing of the dataset is considered unreliable (see Appendix B regarding data processing from raw data (count/s) to physical units). c-d): Energy spectrograms of the simulated ionospheric ion intensity, in the reference frame of the spacecraft, from simulations which made use of the fields from the MHD model of Jia et al. (2009) (panel c) and the hybrid model of Leclercq et al. (2016) (panel d). e) Energy spectrograms of the simulated thermal Jovian ions intensity, in the reference frame of the spacecraft, from simulations which made use of the fields from the MHD model of Jia et al. (2009). The dashed white horizontal line in panels c-e) represents the energy limit (15 eV) below which the processing of the PLS dataset is considered unreliable. The dashed black/white vertical lines show the time of magnetopause crossings (MP) and of closest approach (CA).

606 number density of Jovian ions obtained from an ad hoc simulation in which
607 the fields from the MHD model were used. The Jovian magnetospheric ion
608 population was assumed to be constituted of only H^+ and O^+ . We ran a
609 simulation where the Jovian test particles were injected in all planes of a sim-
610 ulation box with size $20 R_G \times 20 R_G \times 20 R_G$ (in the X, Y and Z directions,
611 respectively) with Ganymede in the center. Test particles were launched
612 assuming a bi-Maxwellian velocity distribution (one in the X-direction and
613 one in the YZ-directions). Both distributions had a temperature of 360 eV
614 (Neubauer (1998)) and were centered at 0 km/s for the YZ-directions and at
615 the corotation velocity of 140 km/s for the X-direction. Plasma composition
616 was assumed to be 87% O^+ and 13% H^+ . In order to reproduce the number
617 density of 4 cm^{-3} of the bulk population outside the plasma sheet (Kivelson
618 et al. (2004)), the density of O^+ was set to 3.48 cm^{-3} , and that of H^+ to 0.52
619 cm^{-3} . Test particles were followed either until they hit the moon or until
620 they crossed any of the boundary planes. A simulation with the same input
621 conditions for the Jovian plasma was performed using the fields from the
622 hybrid model, and the results were confirmed to agree very well with those
623 obtained using the fields from the MHD model.

624 Before 18:50 UTC and after 19:10 UTC the simulations show that the
625 plasma is primarily of Jovian origin and the modeled electron density agrees
626 very well with previous Voyager and Galileo observations (Kivelson et al.,
627 2004) (see Figure 8a). These time periods correspond to when the spacecraft
628 was located outside Ganymede’s magnetosphere: the magnetopause crossing
629 happened at 18:50 UTC inbound and at 19:23 UTC outbound (Kivelson et
630 al., 1997). The Jovian plasma does not gain full access into Ganymede’s

631 magnetosphere in the northern polar region: the plasma number density de-
632 creases after the inbound MP, and increases again to its value outside the
633 magnetosphere at the outbound MP. The discontinuity of the green line in-
634 side the magnetosphere shows that the Jovian test particles did not cross all
635 the ionospheric cells containing the spacecraft trajectory. The simulations
636 demonstrate that the plasma measured by PWS near CA was primarily of
637 ionospheric origin. Ionospheric ions are observed starting from 18:50 UTC.
638 The density profile increases until closest approach, then decreases in the
639 outbound leg. The density maximum near CA is expected in relation to
640 the higher production rate of ionospheric plasma, associated to the higher
641 density of exospheric species (see Figure 2). Most of the ions crossing the
642 spacecraft trajectory are O_2^+ ions, followed by H_2^+ , followed by the other sim-
643 ulated species. The simulated electron density is higher when the fields from
644 the hybrid model are used. This results from the lower electric field derived
645 by the hybrid model, compared to the one obtained in the MHD model of
646 Jia et al. (2009) (see top panel of Figure 4). However, the electron density is
647 consistently underestimated in the simulations, regardless of the electromag-
648 netic fields used as input. When using the fields from both magnetospheric
649 models, the discrepancy between modeled and observed electron density ex-
650 ceeds the order of magnitude and is found to be even higher in the inbound
651 leg of the trajectory, i.e., before 19:00 UTC.

652 *5.1.2. Ion energy distribution*

653 Panels b), c), d) and e) in Figure 8 show the ion intensity plotted on
654 an energy spectrogram as recorded by: the PLS instrument (panel b)), an
655 ionospheric simulation using the fields from the MHD model of Jia et al.

656 (2009) (panel c)), an ionospheric simulation using the fields from the hybrid
657 model of Leclercq et al. (2016) (panel d)) and a simulation of Jovian ions
658 using the fields from the MHD model. The color scale is logarithmic and
659 the range is indicated in the bar adjacent to the three panels on the right.
660 For panels c) and d), only the contribution from ionospheric ions is shown.
661 Similarly to findings in panel a), energy spectrograms attest that ionospheric
662 ions dominate from the time of the first MP crossing to 19:10 UTC. In the
663 PLS spectrogram (panel b), after 19:10 UTC, a “tail” of plasma (orange/light
664 yellow) emerges from the lower energy limit (15 eV). Its energy increases
665 over time (while the intensity decreases) in a similar fashion to the bulk
666 ion population after 19:02 UTC. Key features of panel b) are seen also in
667 panel c). These include: the relative variation in energy of the ion bulk
668 population over the whole flyby, which follows a remarkably similar trend to
669 the measured values, and the “tail” of plasma after 19:10 UTC. Discrepancies
670 between panels b) and c) concern the overall ion intensity and the ionospheric
671 population energy near CA, which are lower in the simulation. Panel c)
672 exhibits the presence of two ion populations, characterized by two different
673 energies along the flyby via two distinctive tails outbound. The population
674 with higher energy includes heavy ions, such as O_2^+ , O^+ , H_2O^+ , OH^+ . The
675 population with lower energy includes light species, i.e. H_2^+ and H^+ . The
676 reader is referred to Figure D.14 in Appendix D to visualize the contribution
677 from each individual ionospheric species to the energy spectrum. In panel
678 d), the energy of the ion population over time is found to vary before CA,
679 in a similar way to panels b) and c). However, after CA the ion energies
680 do not exhibit a double tail as seen in the PLS observations (panel b)).

681 Heavy and light species do not exhibit a dichotomy in the spectrum shown
682 in panel d). The difference between panels c) and d) originates solely in the
683 configuration of \mathbf{E} and \mathbf{B} around Ganymede, which fully determines the ion
684 motion according to Equation 3.

685 We note that for both simulations, the majority of the ion population near
686 CA is found below the energy threshold of the PLS instrument. Most likely,
687 ions were accelerated by a spacecraft potential $V_{S/C}$, and their detection by
688 PLS depended on the sign and strength of $V_{S/C}$. We cannot draw further
689 conclusions on this matter, however, owing to the lack of constraints on the
690 spacecraft potential during the G2 flyby.

691 In summary, we find that: (1) ionospheric ions dominate within the mag-
692 netosphere of Ganymede during the G2 flyby (up to $\sim 19:10$ UTC); (2) the
693 modeled electron number density is underestimated compared with PWS
694 observations, regardless of the electromagnetic field configuration chosen to
695 solve the equations of motion of the ion species; (3) our simulations driven
696 by the electromagnetic field from the MHD model (Jia et al., 2009), repro-
697 duce very well the PLS energy distribution but underestimate the particle
698 intensity.

699 *5.1.3. Ion drift velocities*

700 Taking the moments of order 1 from the ion intensity measured by PLS,
701 we can derive the parallel and perpendicular components of the ion bulk ve-
702 locities (with respect to the magnetic field) along the trajectory. We have
703 compared the bulk velocity profiles from the simulations driven by the MHD
704 model, with those obtained from PLS during G2 (Frank et al., 1997b). The
705 results of this analysis are shown in Figure 9 for O_2^+ and O^+ . Frank et al.

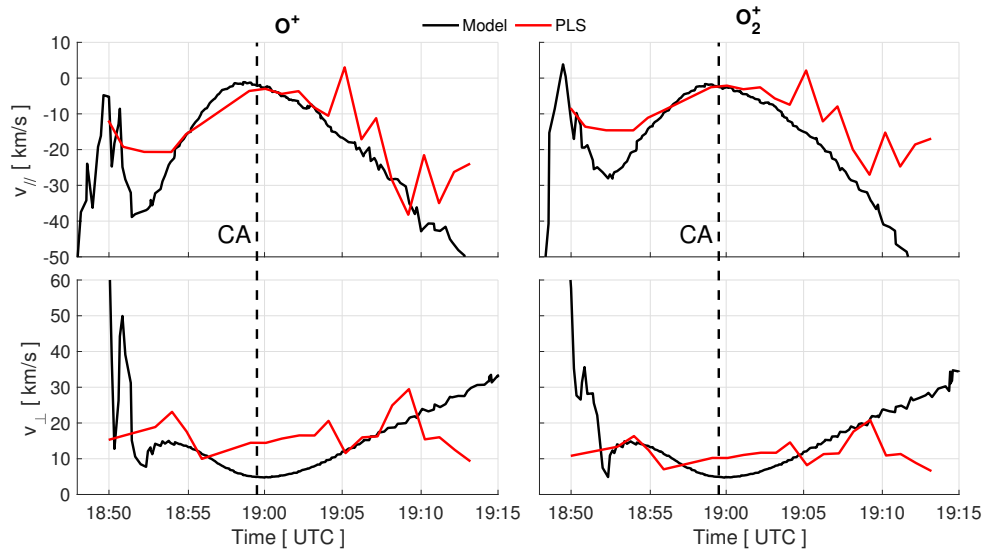


Figure 9: Top: Parallel (with respect to the local magnetic field) bulk velocity component for O^+ (left) and O_2^+ (right) along the G2 trajectory, as obtained from the ionospheric model (black curve) and the PLS instrument (red curve). The PLS profile is originally from Frank et al. (1997b), who assumed only H^+ to calculate the moment, and was adapted to an ionosphere composed purely of O^+ (left panel) or O_2^+ (right panel). Bottom: Same as for the top panels, but for the perpendicular component of the bulk velocity (with respect to the local magnetic field). The modeled results are from simulations driven by the electric and magnetic fields from the MHD model of Jia et al. (2009).

706 (1997b) assumed the plasma to be composed only of H^+ ions, in an attempt
707 to match the electron number density measured by the PWS instrument for
708 the G1 trajectory (Gurnett et al., 1996). Vasyliūnas and Eviatar (2000) rein-
709 terpreted the observed ion flux as being composed of O^+ ions. Besides the
710 difficulties of having mainly H^+ in Ganymede’s magnetosphere, their reinter-
711 pretation was motivated by the higher electron density measured by PWS
712 at G2 (Eviatar et al., 2001). Using a multi-fluid MHD model of Ganymede’s
713 magnetosphere, Paty et al. (2008) provided yet another interpretation of the
714 PLS observations. In their model, they found O^+ to be present with energies
715 below the instrument’s threshold. As a result, this ion species would have
716 not been measured by the instrument. In contrast, in their model the energy
717 range of H^+ ions is mostly above the threshold, so they deduced that H^+ was
718 the species that would have been observed by the instrument. Our results
719 differ from those obtained by Paty et al. (2008). In our model, H^+ reaches
720 a maximum energy of about 1 eV near CA (the yellow part at the bottom of
721 panel c) in Figure 8), which is well below the threshold of the PLS instru-
722 ment, and O^+ reaches approximately 20 eV (the spectrogram shown in panel
723 (c) of Figure 8 incorporates all ionospheric species, so the contribution from
724 each individual species cannot be seen; individual contributions are shown in
725 Appendix D). This trend is opposite to that obtained by Paty et al. (2008),
726 who found H^+ to be above the energy threshold and O^+ below. It is not
727 trivial to explain the difference between the findings of Paty et al. (2008)
728 and our model, considering that the two models are very different in their
729 assumptions and in their approach.

730 The results of the ionospheric model fully rely on the fields used, and we

731 note that these come from magnetospheric models which were quite different
732 in nature compared to the MHD model of Paty et al. (2008). For starters,
733 the MHD model of Jia et al. (2009) is single-fluid (O^+), while that of Paty
734 et al. (2008) is multi-fluid (O^+ and H^+). The former calculates the fields on a
735 spherical grid with very high resolution close to the surface (down to 26 km),
736 while the latter implements a Cartesian grid with the highest resolution being
737 about 120 km close to the moon. The plasma properties at the ionospheric
738 boundary are also different between the two models: Jia et al. (2009) used
739 a density of 550 amu/cm^3 , while Paty et al. (2008) set this parameter to
740 5200 amu/cm^3 with a ratio of 4:1 between O^+ and H^+ . Furthermore, Paty
741 et al. (2008) did not include ionospheric species other than H^+ and O^+ and
742 thus, could not model and/or comment on the contribution of other species
743 (i.e., O_2^+ , etc.) which are considered in the present work. Hence, it is not
744 surprising that the findings from the ionospheric model differ from those from
745 the MHD model of Paty et al. (2008).

746 According to our model, the majority of ions observed by PLS were O_2^+
747 ions (see Appendix C), which populate the higher energy portion of the spec-
748 trogram. In Figure 9, we show the comparison for the velocity components
749 only for O^+ and O_2^+ as these two species were found to provide the best
750 agreement with PLS observations, which were adapted to assume only a sin-
751 gle ion species, either O^+ (left panel) or O_2^+ (right panel). Near CA, O_2^+
752 seems to provide the best agreement between observations and simulations,
753 while after CA O^+ (and other species similar in mass, such as H_2O^+ and
754 OH^+ [not shown]) seems more suitable. Note, however, that the comparison
755 is limited as no error bars were provided for the observed drift velocities.

756 We also note that the model reproduces better the parallel component of
757 the plasma velocity than the perpendicular component. In particular, near
758 CA the ionospheric model underestimates the perpendicular component by a
759 factor of 2, for a pure O_2^+ ionosphere (bottom, right panel in Figure 9), and
760 by a factor of 3, for a pure O^+ ionosphere (bottom, left panel in Figure 9).
761 These comparisons suggest that from 18:55 UTC till around CA approach
762 the plasma observed by the PLS instrument was O_2^+ (or a mixture of O^+ and
763 O_2^+ , which provides an equally good fit [not shown]), while after CA it was
764 most probably a mixture of O_2^+ , O^+ and lighter ionospheric species, such as
765 H_2^+ , which is dominating at high altitudes.

766 To understand further the discrepancy in the perpendicular component
767 near CA between PLS data and the simulations, we have compared the Carte-
768 sian components of the velocity. We have used the profiles from Frank et al.
769 (1997b) and adapted them assuming a pure O_2^+ ionosphere, instead of H^+ ,
770 as the former species is not only the dominant one found in the model, but
771 also seems to give the best agreement with the observations. The results are
772 shown in Figure 10 for the time of flyby near CA. During this period, the
773 spacecraft was flying less than 1000 km above the moon's surface, making its
774 closest approach at 261 km. PLS observed ionospheric ions to move at slow
775 speed in the corotation direction (positive X), and in the anti-Jovian direction
776 (negative Y). At closest approach the mean velocity in the Z-direction was 0
777 km/s, meaning that the ions were observed to move purely in the positive X
778 and negative Y direction. Comparing the PLS profiles with those obtained
779 from our model in Figure 10 suggests that the discrepancy in the velocity
780 comes mainly from the negative Y component. In the model, the ions move

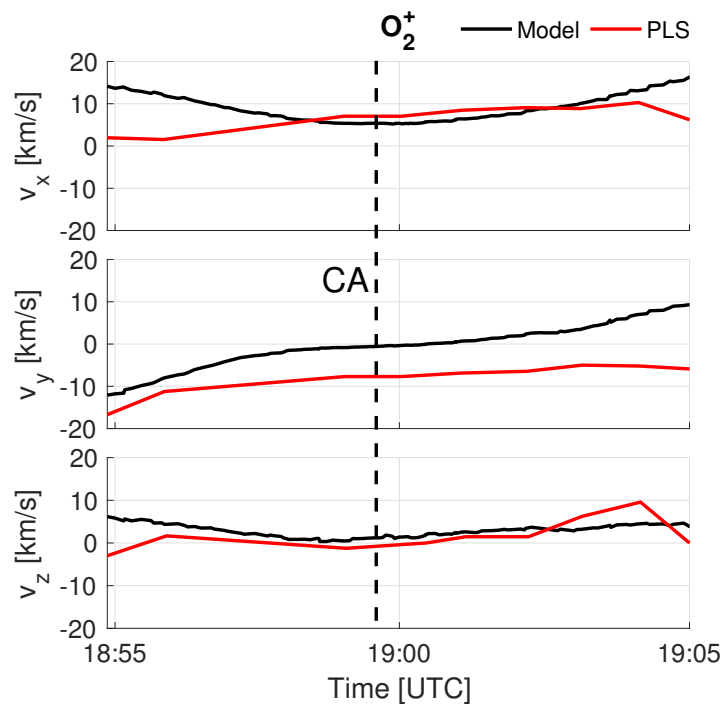


Figure 10: Cartesian components of the mean O_2^+ velocity as found by our model (black curve) and the PLS instrument (red curve), assuming the latter recorded only this ion species.

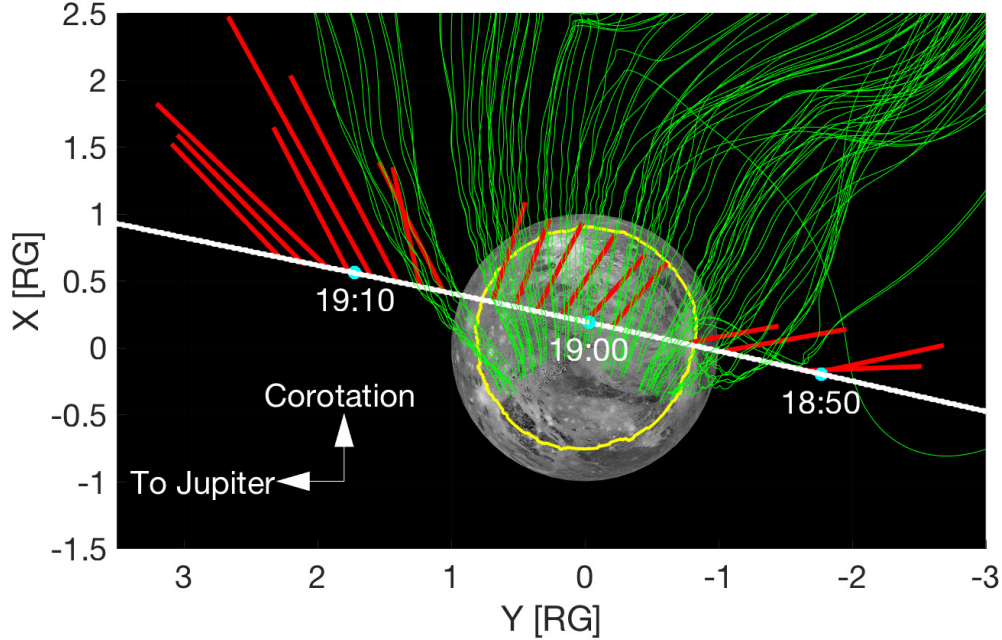


Figure 11: White, bold line: Trajectory of the spacecraft for the G2 flyby. Red lines: Bulk velocity vectors as observed by the PLS instrument (Frank et al., 1997b). Green curves: Selection of O_2^+ test particle trajectories which intersect the path of the spacecraft. Yellow circular line: Northern boundary between open and close magnetic field lines.

781 only in the positive X direction, and do not drift in the anti-Jovian direction.
 782 Figure 11 helps to visualize this finding. Superposed along the spacecraft tra-
 783 jectory are the mean velocity vectors derived by PLS (Frank et al., 1997b)
 784 (red lines), and a selection of O_2^+ test particle trajectories which cross the
 785 spacecraft trajectory (green curves). By inspection of Figures 9 and 10 we
 786 conclude that the perpendicular component missing in the simulations is de-
 787 termined by an ion flow in the anti-Jovian (negative Y) hemisphere which is
 788 absent in the ionospheric model.

789 *5.2. Discussion on the model-observations comparison for G2*

790 The ionospheric model underestimates the electron density irrespective
791 of the fields used to run the simulation (see Section 5.1.1). This discrepancy
792 is highest in the inbound leg of the flyby. For the simulation which uses the
793 fields from Jia et al. (2009), the discrepancy is approximately a factor of 30
794 at 18:52 UTC and progressively reduces to a factor of 5 near CA. The same
795 simulation provides, however, a very good agreement with observations in
796 terms of the ion energy distribution (see Section 5.1.2). Therefore, the fields
797 from this model seem to provide an accurate description of the field configu-
798 ration during the G2 flyby and not to be responsible for the underestimation
799 of the number density. To explain the discrepancy in the ionospheric number
800 density between our model and the observations, two concrete possibilities
801 are therefore left:

- 802 • The underestimation of the ionization frequency;
- 803 • The underestimation of the number density of exospheric species.

804 Photo-ionization depends on the photo-ionization cross-sections, which
805 are well known within 15%, and on the solar flux which should be known
806 within a factor of 2 or less. Hence, uncertainty on photo-ionization cannot
807 be the main reason for the discrepancy in the electron number density. For
808 reference, over the solar cycle, the ion production rates increase by less than
809 a factor of 2. The ionization process from the impact of energetic Jovian
810 electrons is less-constrained as we do not know the energy and spatial distri-
811 bution of this population inside Ganymede's magnetosphere. In our model,
812 the ionization frequency is assumed to be constant everywhere in the region

813 of open magnetic field lines. This is likely not the case, as suggested by
814 the non-uniform location of aurora reported by McGrath et al. (2013) and
815 Molyneux et al. (2018). However, it is very unlikely that the flux of energetic
816 Jovian electrons is 10 times higher or more compared to what we assumed
817 in our model. If else, the flux of these electrons - constrained by Galileo
818 observations outside Ganymede's magnetosphere - should be reduced inside.
819 We conclude that an underestimation of the density of exospheric species is
820 most likely the reason for the low ion densities provided by the ionospheric
821 model . Leblanc et al. (2017) fine-tuned the surface sputtering rate in order
822 to match the column density of O₂ estimated by Hall et al. (1998). As a re-
823 sult, they obtained an exosphere which is dominated by O₂ near the surface,
824 with a mean density of $5 \times 10^7 \text{ cm}^{-3}$. Hall et al. (1998) derived the column
825 density by combining three observational constraints: the aurora brightness
826 measured by the Hubble Space Telescope, the electron density measured by
827 PWS along the G1 trajectory and the upper limit on the far-UV absorption
828 optical depth derived by the UV Spectrometer of the Voyager spacecraft dur-
829 ing a stellar occultation event (Broadfoot et al. (1979)). By combining this
830 set of observational constraints, Hall et al. (1998) assumed not only that there
831 is no time variation, but also that the section of exosphere which was studied
832 during the stellar occultation in 1979 was the same, in terms of density, as
833 that found in the region where aurorae are generated. However, all models
834 of Ganymede's exosphere suggest that the distribution of exospheric species
835 is not uniform across the surface due to the sources of production (sublima-
836 tion and ion sputtering), which do not occur uniformly on the surface. In
837 addition, most of the electron population measured by PWS during G1 and

838 G2 is of ionospheric origin. Hence, a large part of these electrons may not
839 be energetic enough to excite auroral emissions. We argue that the source of
840 energetic electrons at the origin of aurora comes from the Jovian magneto-
841 sphere, and that therefore the electron densities used in Hall et al. (1998) to
842 estimate the oxygen abundance are overestimated. The aurora brightness is
843 proportional to, amongst other parameters, the energetic electron flux and
844 the neutral density. Therefore, the same aurora observed by HST can be
845 matched by decreasing the electron flux and increasing the molecular oxygen
846 density. Further simulations of the exosphere are needed in order to make a
847 more quantitative statement on how much the exospheric density needs to be
848 increased. Furthermore, being indirectly related to the same production pro-
849 cess, an increase in the density of O₂ would imply an increase in the density
850 of H and H₂ in the exosphere. This could bring the H Lyman- α brightness
851 calculated with the model of Leblanc et al. (2017) in line with that observed
852 by the UV spectrometer on board the Galileo spacecraft, while currently the
853 brightness in the model is underestimating the observations by more than
854 one order of magnitude.

855 We calculated that by boosting by a factor of approximately 10 the col-
856 umn densities of all species, and still assuming a constant electron-impact
857 ionization frequency in the polar regions, the derived ionospheric number
858 densities match the observations along the Galileo G2 trajectory. This re-
859 sults in an O₂ column density around $3 \times 10^{15} \text{ cm}^{-2}$, which is slightly above
860 the upper limit estimated by Hall et al. (1998), but most likely within the
861 error bars.

862 In terms of energy distribution, our simulation results are sensitive to the

863 electromagnetic field configuration used to run the simulation (see panels
864 c) and d), Figure 8). To assess the sensitivity of the results to the spatial
865 resolution of the electric and magnetic fields, we ran two simulations using
866 the fields from the MHD model of Jia et al. (2009): one with a spatial
867 resolution for the fields of $0.1 R_G \equiv 263.41$ km (low resolution), and one with
868 a resolution of $0.05 R_G \equiv 131.7$ km (high resolution). The resulting maps
869 are very similar between the two simulations (not shown), indicating that
870 the resolution does not affect significantly the outcome of the simulations.
871 In panel c) of Figure 8, the spectrogram shows results from a simulation
872 driven by fields with high resolution. The spectrogram generated by the
873 simulation with low resolution looks similar, and all the key features, also
874 seen in the observed spectrum (panel b), Figure 8) are also present. For the
875 electron density along the G2 trajectory, the resulting profiles are similar
876 when using the low and high resolution fields of the MHD model. The higher
877 resolution fields lead to a slightly increased density near CA, but not enough
878 to justify the discrepancy with the values derived from PWS measurements.

879 By comparing Figures 9 and 10 in Section 5.1.3, we associated the dis-
880 crepancy, between our model and PLS observations, in the perpendicular
881 drift velocity near CA with a flow in the negative Y direction. This flow was
882 observed by PLS during the flyby but not reproduced by our model. This
883 perpendicular flow indicates that cross-field currents flow in Ganymede's po-
884 lar ionosphere, suggesting that there is enough resistivity provided by the
885 neutral species. These currents show that the ionosphere is not spatially ho-
886 mogeneous. The hybrid model of Leclercq et al. (2016) and the MHD model
887 of Jia et al. (2009) both assumed a spherically symmetric ionosphere due to

888 the current lack of knowledge on the spatial distribution of the ionospheric
889 plasma. As a result, these currents, being generated by an asymmetry in
890 the spatial distribution, are not reproduced in the magnetospheric models.
891 A current flowing from the Jupiter-facing (positive Y) to the anti-Jupiter
892 (negative Y) hemisphere suggests that the production of plasma is more in-
893 tense in the Jovian-facing hemisphere, and the charge disparity between the
894 two hemispheres sets up a potential difference which induces a Pedersen cur-
895 rent. This asymmetry in the production rate can be explained by a denser
896 exosphere in the Jovian-facing hemisphere or by a stronger flux of magne-
897 toospheric electrons which are able to ionize the neutral exosphere. Leblanc
898 et al. (2017) found that for the G2 epoch the O₂ density was highest in the
899 Jupiter-facing hemisphere, which supports our argument. Another possibility
900 to explain a denser exosphere in one hemisphere is to have a more intense, in
901 terms of flux or energy, sputtering process by Jovian magnetospheric ions. In
902 this picture, the flux of magnetospheric electrons would be enhanced, leading
903 to a higher production rate of ionospheric plasma. This process is currently
904 being investigated, but beyond the scope of the present study. Moreover,
905 this argument provides an explanation for the enhanced brightness of aurora
906 emissions in the Jovian-facing hemisphere observed by HST and reported in
907 McGrath et al. (2013) and Molyneux et al. (2018) .

908 **6. Conclusions**

909 We have presented the first three-dimensional model of Ganymede's iono-
910 sphere, assuming a background configuration of the moon corresponding to
911 that during the G2 flyby. We found that O₂⁺ is the most abundant species,

912 followed by O^+ , H_2^+ and H_2O^+ , despite finding the first two species mainly im-
913 pacting the moon’s surface. For other species, the majority of the population
914 escapes the magnetosphere through the Alfvén wings or in the direction of
915 corotation of the Jovian plasma. The dominance of O_2^+ and O^+ ions as source
916 of surface impact is related to the distribution of O_2 , which is concentrated
917 very close to the surface, unlike for other neutral species. We found that the
918 ion outflow velocities measured by PLS during G2 (Frank et al., 1997b) are
919 most consistent with O_2^+ ions escaping Ganymede’s magnetosphere in the
920 direction of corotation. This differs from the interpretation of Frank et al.
921 (1997b), who assumed H^+ to be the only species, from the interpretation of
922 Vasyliūnas and Eviatar (2000), who reinterpreted the PLS data as being an
923 outflow of O^+ , and from that of Paty et al. (2008) who found both species
924 to be present in the ionosphere, but H^+ to be the only one detected by the
925 PLS instrument.

926 By comparing the results from our model with the electron density pro-
927 files recorded by PWS and the ion energy spectrogram recorded by PLS, we
928 confirmed the ionospheric nature of the plasma starting from the inbound
929 magnetopause crossing, until approximately 19:10 UTC. We also obtained a
930 very good agreement with the ion energy distribution measured by the PLS
931 instrument when using the fields derived by the MHD model of Jia et al.
932 (2009) as input. However, our simulation predicts lower intensities overall
933 and lower energies near closest approach, interpreted as a velocity in the nega-
934 tive Y direction which is not reproduced in our model. This “missing current”
935 from positive to negative Y may be explained by considering that the mag-
936 netospheric models considered in this work implemented a spatially constant

937 and temporally uniform ionosphere, which prevent non-uniform distributions
938 to form. A non-uniform distribution would set up a potential difference which
939 in turn would induce cross-field currents, assuming a resistivity high enough
940 to sustain this current, which is provided by the neutral atmosphere. The
941 cross-field motion observed by PLS indicates that the ionosphere is not uni-
942 form, and suggests that the plasma production rate might be higher in the
943 Jovian-facing hemisphere. This could be explained by an increased flux of
944 magnetospheric plasma, which boosts the surface sputtering (and so the den-
945 sity of neutral species) and the ion production through electron impact, or
946 by an increased exospheric density related to the accumulation of O₂ in the
947 Jovian-facing hemisphere, as found by the exospheric model of Leblanc et al.
948 (2017).

949 The discrepancy between our simulations and the values obtained by PWS
950 in terms of the electron number density is likely to be caused primarily by an
951 underestimation of the exospheric densities (see Section 5.2). We estimated
952 that the density of O₂ should be approximately a factor of 10 higher (in
953 terms of column density) in order to match the observations from PWS. This
954 would reduce the ions mean free path, and potentially require the inclusion
955 of collisions close to the surface. Furthermore, we would have to assess if
956 energetic electrons undergo any significant energy degradation close to the
957 surface. However, we have checked that the exosphere remains optically
958 thin to EUV radiation (assuming a boosted exosphere). The results of our
959 model suggest that in order to improve further the comparison with Galileo
960 data from the G2 flyby, magnetospheric models should take into account
961 the asymmetries in the ionosphere, which are generated by the spatially non-

962 uniform production mechanisms and the non-uniform exosphere. Ultimately,
963 a self-consistently coupled model of the ionosphere and magnetosphere should
964 address that.

965 Based on the outcome of the comparison between the model output and
966 observations, the exospheric density profiles seem to be underestimated. In
967 the future we plan to implement a physically suitable modification to the
968 exospheric configuration that would reconcile modeled and observed iono-
969 spheric densities. This would help to fully validate the model against Galileo
970 plasma observations and confirm the usefulness and relevance of our model
971 in preparation to the JUICE mission, especially for the Ganymede phase
972 when the spacecraft will be in orbit around the magnetized moon. For ex-
973 ample, the 3D electron density distribution could be thus used to select the
974 optimal operating modes of the Radio Plasma Wave Instrument (RPWI). In
975 addition, the density and velocity maps for different ions could be not only
976 directly relevant to the instrument teams, but also used as inputs for space-
977 craft simulations to calculate quantities, such as the radiation dose received
978 by the spacecraft inside Ganymede's magnetosphere. Furthermore, we plan
979 to assess the surface sputtering rate due to ionospheric plasma precipitation
980 and compare these with the contribution from Jovian ions. These results
981 could be implemented in exospheric models to include the ionospheric source
982 of neutral species in the exosphere. Moreover, our model allows to calculate
983 the production rate and density map of Energetic Neutral Atoms (ENAs) by
984 charge-exchange between ions and neutral species. This could be relevant
985 to the Particle Environment Package (PEP) instrument which will assess
986 the properties and distribution of these particles around Ganymede. Finally,

987 a self-consistently coupled ionosphere-magnetosphere model could be highly
988 critical for the interpretation of the magnetic field data measured by J-MAG
989 in the moon’s environment.

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1006 flux data set (<http://lasp.colorado.edu/see/>).

Appendix A. Identifying input-driven features in the 2-D maps of number density, bulk velocity and temperature

Figure 7 shows 2-D maps of the number density, bulk velocity and temperature for O_2^+ obtained using, as input, the electromagnetic field from the hybrid model of Leclercq et al. (2016) (hereafter referred as ‘HYB16’). Figure A.12 shows the same maps obtained using the electromagnetic field from the MHD model of Jia et al. (2009) (hereafter referred as ‘MHD09’).

Many results discussed in Sections 4.2.1– 4.2.3 apply also for the results obtained using the MHD model. These include: (1) the plasma confined mainly within the Alfvén wings and the closed magnetic field lines, (2) the escape through the wings and the corotation direction at low latitudes, (3) the low velocity/temperature inside the wings, and the high velocity/temperature at the wings’ boundaries and in the equatorial region. Overall, implementing either of the two sets of fields leads to the same global convection pattern of the ionospheric plasma and the same order of magnitude for all the first ion moments shown in Figure 7 and A.12.

The differences between HYB16 and MHD09 concern primarily small scale features. For example, the ‘string-like’ features that appear in HYB16 in the polar regions are absent in MHD09. As explained in Section 4.2.1, these are to be considered as noise in the electric field generated by the hybrid model in relation to the limited resolution of the grid close to the surface, which does not appear to be sufficiently refined to physically resolve the field configuration. Another difference concerns the asymmetry in the YZ plane in the bulk velocity and temperature. For MHD09, velocities are higher in the anti-Jovian hemisphere at low latitudes, while for HYB16 this

is not the case (except close to the surface where speeds are small in both hemispheres). Furthermore, for HYB16 there is no preferential drift in the clockwise direction like there is when using the MHD model, which can be seen also from the less defined arrow directions in panel f) of Figure 7 compared with panel f) in Figure A.12. Finally, in MHD09 the plasma in the polar regions appears to feel a greater pressure in the corotation direction, which limits the upward spread of plasma along the Alfvén wings. In other words, the plasma close to the surface in the polar regions in MHD09 is seen to flow predominantly in the x-direction, contrarily to HYB16, in which the plasma is seen to spread more in altitude. A comparative study to interpret these difference is worth undertaking, but beyond the scope of this work.

Either set of input fields leads to the same conclusions presented in this manuscript, which supports their validity.

Appendix B. Processing of PLS data

Here we describe how the PLS data shown in panel b) of Figure 8 has been processed. PLS is an ion and electron particle detector, which is part of the Galileo instrumentation (Frank et al. (1992)). In this work only the ion data collected by PLS is of importance. PLS consists of seven detectors, each of which detects particles coming from different parts of the sky. They are oriented in such a way that during approximately one spin (~ 20 s) of the Galileo spacecraft the whole sky is scanned. In addition to scanning over directions, each PLS detector also scans over energy-per-unit charge (E/Q), from 0.9 eV to 52 keV.

Due to the malfunction of Galileo’s main antenna the data rate was very

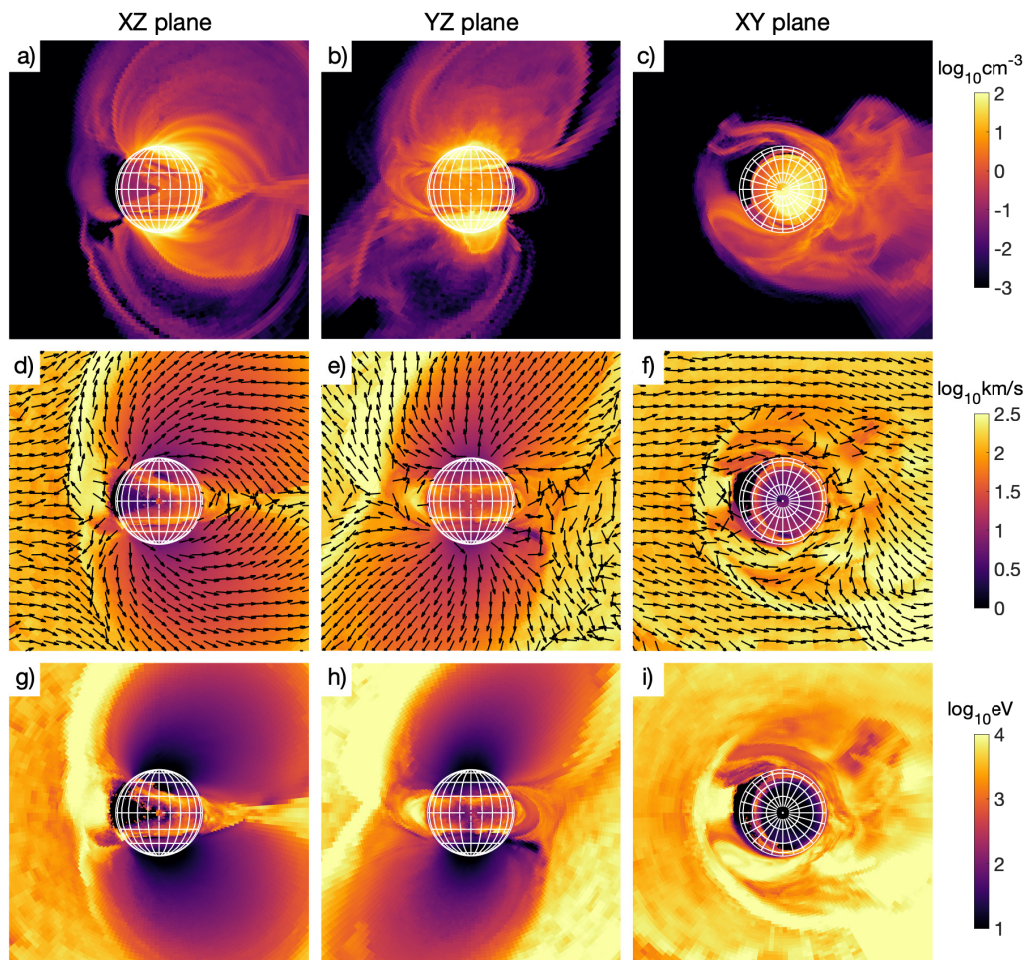


Figure A.12: Maps of the distribution moments for O_2^+ with Ganymede at 11 a.m. in Jupiter's solar local time. All color scales are logarithmic. Top row: Number density. Middle row: Bulk velocity. Bottom row: Bulk temperature. For a generic plane "AB", 'A' points to the right and 'B' points up.

limited during the whole mission. Hence, for each spin only a limited part of the data was transmitted, resulting in an incomplete coverage of the sky in both energy and direction. Additionally, the PLS instrument was also affected by penetrating electrons that entered the detector through the shielding and created noise.

The PLS data shown in Figure 8 has been processed in several steps to compensate for the poor coverage in time, energy and background noise. The processing of the data was done using the CCATI software, originally developed by Markus Fraenz (<http://www2.mps.mpg.de/projects/mars-express/aspera/ccati/>). First, the raw PLS data was obtained from NASA's Planetary Data System (PDS), in units of counts per second. Every data point has a tag representing the time, energy bin detector number and sector number. The latter represents the spin angle at which the measurement was made. Next, data values for one detector, for which the current, previous and next time steps that have the same energy tag, but a different sector number, are averaged. Subsequently, for each time step a cubic spline interpolation is applied to fill in the empty energy bins. After that, the noise is removed as follows. For each time step, the average and the standard deviation are extracted from the count rate in the energy bins of the four highest energy bins that have non-zero values. The standard deviation, multiplied by 0.2, is added to this average. The result is then subtracted from all energy bins of the corresponding time step, to remove the background noise. This is comparable to earlier PLS studies, which have also used the count rate in the highest energy bins to estimate the background noise [Frank and Paterson (1999); Paterson et al. (1999)]. Next, the data units are converted from counts/s to intensity (also

called differential flux) in $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{eV}^{-1}$. This is done by multiplying the data with the ‘chi-factor’ . The chi-factor was obtained by the PLS team from calibration experiments in laboratory and provided to the PDS. As a final step, averaging in time is performed together with averaging over the seven detectors. This is done using ‘box car’ averaging, meaning that the time frame is first divided in equally sized bins. Then all the values in each energy-time bin (taken from all the detectors) are summed up and this sum is divided by the number of values in the energy-time bin. Here averaging is done over bins of 60 seconds in length.

The data obtained during the G2 flyby has been obtained with two different scanning modes: one below 15 eV and one above 15 eV. Because of uncertainties in the processing of the data of the low energy scans we only consider the processed data above 15 eV to be reliable.

Appendix C. Volume mixing ratio along G2 flyby

We report in Figure C.13 the volume mixing ratio of ionospheric species calculated along the G2 flyby from a simulation with input electric and magnetic fields from the MHD model of Jia et al. (2009). O_2^+ dominates amongst the ionospheric species from around 18:37 UTC to 19:14 UTC (except for a very short period around 10:08 UTC). The semi-transparent red box from 18:50 UTC to 19:13 UTC indicates the time range from which Frank et al. (1997a) calculated the second moment of the plasma distribution measured by the PLS instrument. Within this time range, our simulation finds that O_2^+ is the dominant species, followed by H_2^+ .

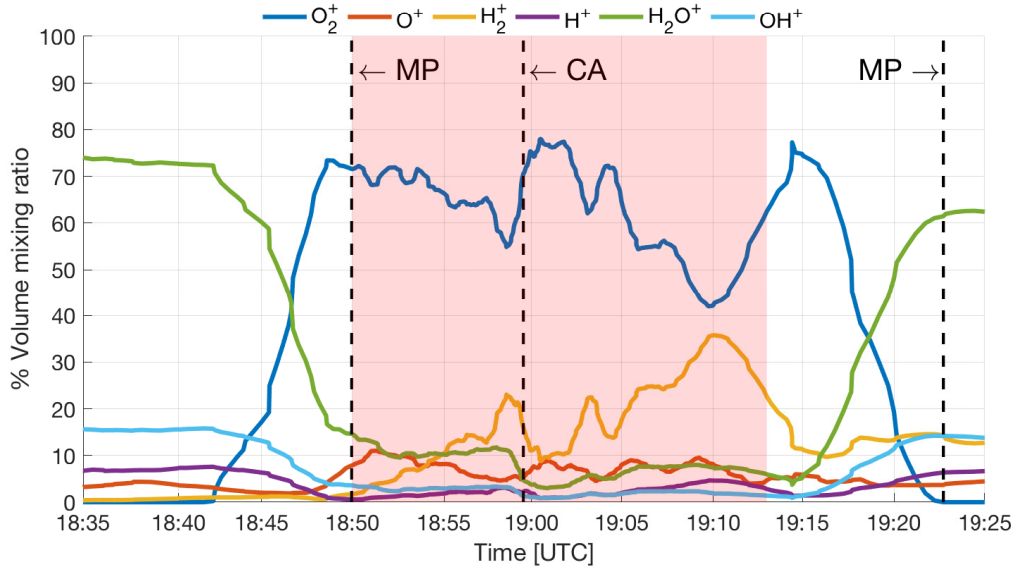


Figure C.13: Volume mixing ratio of ionospheric species calculated along the G2 flyby. The black dashed vertical lines indicate the crossing times of the magnetopause (MP) and closest approach (CA). The semi-transparent red box indicates the time range from which Frank et al. (1997a) calculated the first moment of the plasma distribution measured by the PLS instrument.

Appendix D. Energy spectrum decomposition

We report in Figure D.14 the energy spectrum along the G2 flyby from: the PLS instrument (panel a), the ionospheric model considering all ionospheric species (panel b) and the ionospheric model separating the contribution from each different ionospheric species (panels c-h). The input electric and magnetic fields were taken from the MHD model of Jia et al. (2009).

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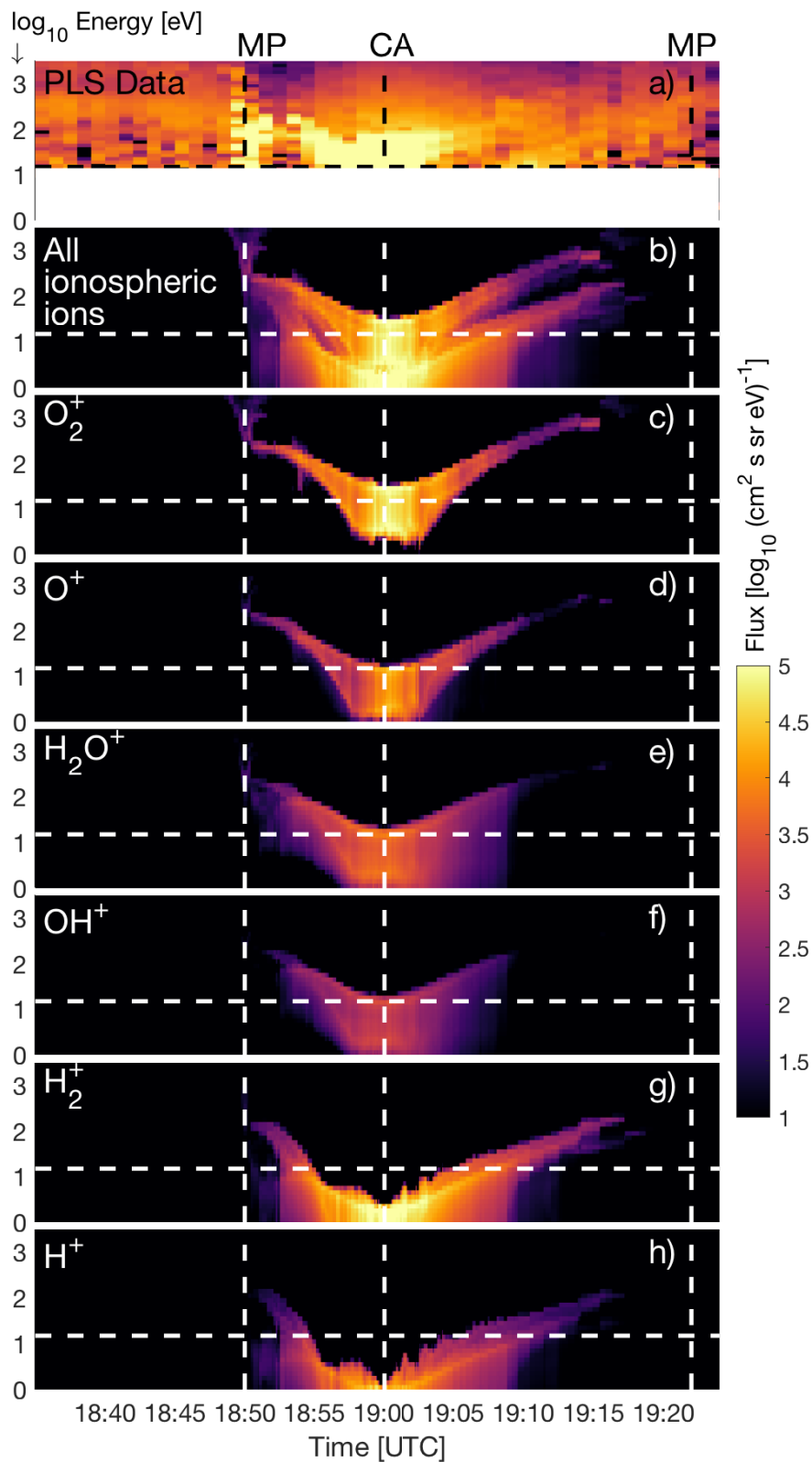


Figure D.14: Energy spectrum along the G2 flyby from: the PLS instrument (panel a), the ionospheric model considering all ionospheric species (panel b) and the ionospheric model separating the contribution from each different ionospheric species (panels c-h). The colour scale is logarithmic and equal for all panels. The white dashed horizontal lines indicate the energy below which the processing of the PLS dataset is considered unreliable. The white dashed vertical lines indicate the crossing times of the magnetopause (MP) and closest approach (CA).