Preliminary estimation of the detection possibilities of Ganymede's water vapor environment with MAJIS

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Abstract

The exosphere of Ganymede is the interface region linking the moon's icy surface to Jupiter's magnetospheric environment. Its characterization is of key importance to achieve a full understanding of the ice alteration processes induced by the radiation environment. Several scientific instruments that will operate on board the upcoming Jupiter Icy Moons Explorer (JUICE) mission, selected by ESA in the context of its Cosmic Vision programme, have the potential to study Ganymede's exosphere. Among them, the Moons And Jupiter Imaging Spectrometer (MAJIS) will have the chance to investigate the composition of the moon's exospheric components and the emission of water molecules. The exospheric water density profile, as obtained from current models, is a crucial parameter for the estimation of the expected signal to noise ratio related to the actual measurement. In lack of an adequate number of Ganymede's observations from past missions, there is a general

difficulty in constraining current exosphere models which are based, in general, on different scenarios and considerations and often show large discrepancies in the estimated spatial distribution of the neutral environment. In this work, we make a preliminary estimation of the expected IR emission from exospheric water molecules, using different modelled density profiles, and we speculate on the possibility of JUICE/MAJIS to detect it. An exercise on the potential plume detection capabilities of MAJIS is also performed. The first necessary step for performing these calculations is a rough comparison of the existing models of Ganymede's water vapor exosphere. We discuss the characteristics of the neutral environment as derived from different exospheric models available in literature, the role of the ion-surface interactions in the H_2O exosphere generation, and the related implications also in view of future observations. We then use the model outputs to estimate different scenarios for the expected non-Local Thermal Equilibrium (non-LTE) emission from these molecules. The results of this study can be of help during the JUICE observation planning phase.

1. Introduction: general concept and motivation for the current work

Ganymede is the only known moon in the Solar System so far explored to possess an intrinsic magnetic field embedded within a planetary magnetosphere (Gurnett et al., 1996; Kivelson et al., 1996; 1998). The intensity of Ganymede magnetic field, up to ~1,500 nT in the polar regions (Williams et al., 1997), is sufficiently strong to stand off the Jovian plasma flow, as revealed by the measurements of the Energetic Particle Detector (EPD) onboard the Galileo mission (Williams et al., 1992), in the vicinity of the moon and within its magnetosphere (e.g., Paranicas et al., 1999; Williams, 2001). A non-negligible flux of charged particle populations (mainly Hydrogen, Oxygen and Sulfur ions) impacting the moon's icy surface is believed to activate different release processes, such as sputtering and radiolysis (Marconi, 2007; Plainaki et al., 2015; Leblanc et al., 2017). Modeling of the ion circulation around Ganymede has shown that the bulk population of Jupiter's plasma sheet enters

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53 the moon's magnetosphere mainly through the cusps and at low latitudes in the plasma wake

54 hemisphere, most likely through tail reconnection (Poppe et al., 2018). The energetic ions in the keV-

55 MeV range are expected to impact the moon also at regions outside the cusps (see, for instance,

56 Plainaki et al., 2015), inducing ice dissociation and direct sputtering of surface molecules (Bahr et

57 al., 2001; Moore et al., 2007; Teolis et al., 2006, 2017). Laboratory studies revealed that a series of

58 complex surface chemistry processes initiated after ice bombardment by energetic ions, results in the

59 release of H, H_2, O, O_2, OH, and H_2O particles (Johnson, 1990). The characteristics of the energetic

60 particles in the vicinity of the Galilean moons and the release of particles from their icy surfaces have

61 been discussed in the fundamental paper by Cooper et al. (2001). At Ganymede, the ion-induced

62 particle release, together with water sublimation, are believed to generate a tenuous atmospheric

63 envelope around the moon, often referred to as an "exosphere" (e.g., Plainaki et al., 2015). The

64 measurements by the Plasma Science (PLS; Frank et al., 1997b) and Plasma Wave Science (PWS;

65 Eviatar et al., 2001) instruments onboard Galileo, revealed that Ganymede also possesses an

66 ionosphere (Carnielli et al., 2019), consistently with the findings of the Galileo radio occultation

67 experiment (Kliore, 1998).

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69 Globally, the exosphere of Ganymede consists mainly of sputtered H_2O as well as O_2 and H_2 produced

70 through radiolysis (Johnson, 1990); some other minor species are also expected to be released from

71 the surface through sputtering. The global exospheric environment, therefore, is expected to be

72 formed through a complex process driven by the energy and spatial distributions of the Jovian ion

73 populations, depending at the same time on the moon surface characteristics (e.g. temperature,

74 composition) and the particle release properties (yield, initial energy distribution). Ganymede's

75 neutral environment is believed to be mainly collisionless apart a limited region around the subsolar

76 point where collisions may be present (Marconi, 2007). The exosphere of Ganymede is the actual

77 interface between the icy surface of this moon and Jupiter's magnetosphere. Therefore, its

78 characterization is of key importance to achieve a full understanding of the ice alteration processes

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79 induced by the radiation environment, similarly to the case of Europa (see, for instance, Plainaki et

80 al., 2018 and references therein). For example, the deposition of neutral species from the exosphere

81 onto the moon's surface (e.g., deposition of water) will spectrally mask the weathering products or

82 directly start new chemical patterns. Moreover, the efficiency of both surface weathering and particle

83 release from the surface may be reduced by the ionosphere, which is formed by the ionization of the

84 neutral exosphere. In this view, a number of numerical models have been developed to understand

85 the plasma circulation around this moon as well as the generation of its surface-bounded H_2O

86 exosphere (e.g., Marconi 2007; Turc et al., 2014; Plainaki et al., 2015; Shematovich 2016; Leblanc

87 et al., 2017) and ionosphere (Carnielli et al., 2019). Some evidence for the existence of an exosphere

88 around Ganymede was already provided by the Galileo/UVS (Barth et al.,1996), the HST/GHRS

89 (Hall et al.,1998) and HST/STIS (Feldman et al.,2000) instruments. Recently, the Heterodyne

90 Instrument for the Far Infrared (HIFI) on board the Herschel Space Observatory (Hartogh et al., 2013)

91 observed the vapor H_2O environment of Ganymede. These authors found a difference between the

92 H_2O densities observed at the leading and trailing hemispheres of a factor of 10 and they attributed it

93 to surface composition characteristics, although the uncertainty in their measurements is not

94 negligible.

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96 Several scientific instruments that will operate on board ESA's upcoming Jupiter Icy Moons Explorer

97 (JUICE) mission, have the potential to study Ganymede's H_2O exosphere (Grasset et al., 2013; JUICE

98 definition study report[1]). Among them, the Moons And Jupiter Imaging Spectrometer (MAJIS) will

99 investigate the composition and spatial distribution of water and non-water-ice components in both

100 Ganymede's surface and exospheric environment. There is a strong scientific motivation for

101 speculating on the potential of observing Ganymede's H_2O exosphere during ESA's upcoming JUICE

102 mission. In particular, revealing the characteristics of the near-surface H_2O environment along

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[1] http://sci.esa.int/juice/54993-juice-definition-study-report-red-book/

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103 Ganymede's orbit around Jupiter will allow the identification of its source regions and also the

104 efficiency of the particle release from ice, providing at the same time constraints for estimating the

105 energy exchange between the Jovian system and the moon itself. This is due to the fact that the spatial

106 density and energy distributions of Ganymede's H_2O environment reflect the origins of the exosphere

107 generation and the properties of the interaction of the icy surface with the moon's surrounding

108 radiation environment. Indeed, the morphology of the sputtered-H_2O exosphere depends on the

109 topology of the open/closed magnetic field line region, the incident Jovian ion flux and the content

110 of ice contaminants on the surface. In particular, the H_2O molecules released from the surface after

111 its bombardment by Jupiter's plasma and energetic ions follow ballistic trajectories until they return

112 to the surface or they escape or they are lost through ionization or dissociation processes. Upon return

113 to the surface, the H_2O molecules stick there and do not migrate to nearby locations hence remaining

114 confined to their ejection region. This is an important distinction between the H_2O and the O_2

115 exospheric components. In fact, the O_2 molecules, upon return to the surface, they get thermalized

116 (average kinetic energy $\sim k_b T$) and bounce back to continue their ballistic travel. The process of

117 thermal desorption after the re-impacting of the molecules to the surface is repeated many times until

118 O_2 is either dissociated or ionized. Consequently, contrary to the sputtered-H_2O case, the spatial

119 distribution of the O_2 exospheric density is not directly coupled to its production map upon the

120 surface. Since the H_2O molecules lifetime (before loss) is much longer than the average ballistic flight

121 time, and due to the water's sticking to the ice capability, the spatial distribution of the H_2O exosphere

122 maintains the memory of its origins, providing information on the spatial characteristics of the ice –

123 ion interaction as well as on the sputtering efficiency.

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125 There are further scientific motivations for speculating on the potential of observing Ganymede's

126 H_2O exosphere with JUICE. In particular, the observation of spectral emissions through limb

127 scanning near Ganymede's poles, may provide information related to the preferential access of

128 charged particles to the moon's polar caps furnishing important constraints for the surface weathering

129   history. The details of the ion access to Ganymede's surface, although attributed to the moon's

130   magnetic field topology, have been long debated in the scientific community. Smith et al. (1979),

131   based on Voyager observations, and Khurana et al. (2007), based on Galileo imaging (see figure 3 of

132   their paper), explained the presence of observed bright polar caps on Ganymede with sputter-induced

133   redistribution and subsequent cold trapping of water molecules, which result in a newer surface,

134   continuously eroded. In particular, Khurana et al. (2007) pointed out a close correspondence between

135   the open-closed magnetic field lines boundary and the boundary of the Ganymede's polar cap that

136   they interpreted as evidence that the latter is associated with charged particle effects. Khurana et al.

137   (2007) suggested also that the equatorial leading/trailing asymmetry (i.e., the albedo of the leading

138   hemisphere is higher than the trailing one; Clark et al., 1986) was due to the preferential flux of ions

139   onto Ganymede's leading hemisphere due to magnetotail reconnection, an hypothesis that was later

140   confirmed by ion-trajectory simulations by Plainaki et al. (2015) and Fatemi et al. (2016). Numerical

141   simulations of both energetic ion precipitation on Ganymede's surface and sputter-induced exosphere

142   generation (e.g. Jia et al., 2009; Plainaki et al., 2015; Poppe et al., 2018) seem to support such a

143   scenario, with respect to both aforementioned points. In particular, simulations by Plainaki et al.

144   (2015) and Poppe et al. (2018) show a shielded region close to Ganymede (at distances < 1.5 R_G)

145   asymmetrically displaced towards the sub-Jovian trailing hemisphere, with enhancements of lower-

146   energy ion flux along the trailing-side boundaries of Ganymede's Alfvén wings. Moreover,

147   enhancements in the flux on the anti-Jovian leading hemisphere are present (Poppe et al., 2018). It's

148   worth noting, however, that current models depend significantly on a series of physical parameter

149   assumptions which are currently poorly known, mainly due to the absence of an adequate quantity of

150   in situ data and also because their quality in terms of spatial and spectral resolution hinder the

151   inference of the necessary properties. Moreover, Ganymede has been mostly observed by ground-

152   based telescopes so far and for this reason the spatial resolution and coverage of the currently

153   available databases are rather limited. For example, the consideration in the models of the moon's

154   magnetosphere morphology (see, for instance, the different approaches by Paty et al. 2008, Jia et al.

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155   2009 and Fatemi et al. 2016), or the detailed composition of the icy surface (including impurities) has

156   direct impacts in the modeled sputtering and sublimation rates of the surface. For this reason, and

157   despite the numerous kinetic models proposed in literature, we do not have yet the necessary

158   information to disentangle the influence of different mechanisms on the spectral properties of

159   Ganymede's surface.

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161   The spectral properties of the exosphere of Ganymede must be resolved for determining the properties

162   of the space environment of Ganymede and for accurately mapping ion precipitation to the icy

163   surface, a key mechanism linking the moon itself to the Jovian magnetospheric environment. In this

164   paper, we investigate the possibility for MAJIS to observe spectral emission signatures of

165   Ganymede's H_2O exosphere, such as the non-Local Thermal Equilibrium (non-LTE) photon

166   emissions from water molecules, using different modelled density profiles. First, we compare the

167   existing models of Ganymede's water exosphere. We then use these model outputs to estimate the

168   different scenarios for the expected IR emission from water molecules. In particular, in Section 2 we

169   briefly review the generation mechanisms of Ganymede's H_2O exosphere and discuss how the

170   morphology of the neutral environment depends on the properties of the charged particle circulation

171   around the planet. We also discuss the environment characteristics derived by different models. In

172   Section 3 we present the main characteristics of the MAJIS instrument relevant for our investigation

173   and we estimate the expected signal non-LTE photon emission from the water exospheric molecules.

174   Endogenic processes can also contribute to exospheric density enhancements. In particular, ongoing

175   cryovolcanic activity has been identified on Enceladus, and probably on Europa, through the

176   observation of water (gas and ice) plumes (Porco et al., 2006; Sparks et al., 2017). Although no such

177   evidence has been found so far for Ganymede, the JUICE mission offers a unique opportunity for

178   searching for such an activity in geometric configurations not accessible from the Earth's orbit. In

179   this regard, remote observations in visible and near-infrared spectral range at very high solar phase

180   angle (or even in solar occultation geometry, if possible) are the most promising, since a plume

scatters solar light much more efficiently in the forward direction. In Section 4, we try to establish the potential observability of these phenomena with MAJIS, considering different observing study cases representative of different mission phases. In Section 5, we discuss the results of our calculations and present a summary of conclusions together with some future plans to optimize MAJIS observations.

2. Generation of the water vapor exosphere of Ganymede

The role of Ganymede's mini magnetosphere

The plasma-surface interactions guided by Ganymede's intrinsic magnetic field are the main drivers of the H_2O exosphere generation. The major plasma source in Jupiter's magnetosphere is the volcanic-active moon Io which ejects material that becomes dissociated and/or ionized by the solar EUV radiation (Broadfoot et al., 1979), generating predominantly multiply charged Oxygen and Sulfur ions (Bagenal et al. 1996). At Ganymede's distance from Jupiter, the plasma is confined to a low scale height current sheet (also called Jupiter's Plasma Sheet - JPS) cantered roughly around the Jovian magnetic equator (Khurana et al., 2004; 2007). Because of the 10^0 tilt of Jupiter's magnetic field to the planet's rotational axis, the current sheet oscillates up and down Ganymede's orbital plane. Within the plasma sheet and up to a distance of $\sim 10\ R_J$ from Jupiter, the plasma slightly subcorotates at v ~ 150 km/s, whereas at the distance of Ganymede (at about 15.3 R_J from Jupiter) it lags the corotation, in the azimuthal direction, by 37 km/s (Kivelson et al., 2004). At Ganymede, the Jovian magnetospheric plasma is characterized by a thermal component with density, n_e, $\sim$5–20 cm^{-3}, and temperature, T_e, $\sim$ 20 eV plus a suprathermal component with $n_e \sim$0.5–2cm^{-3}, $T_e \sim$ 2keV (Scudder et al., 1981). The bombardment of Ganymede's surface by high energy ions induces radiolysis and direct sputtering of surface molecules that populate the moon's exosphere (Cassidy et al., 2013). The generation and evolution of the exosphere of an icy moon is a complex process that depends on the environment properties (e.g. spectrum and flux spatial distribution of Jupiter's magnetospheric ion

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207 population), the characteristics of the moon's surface (e.g. composition, impurities, temperature), as

208 well as the moon's orbital phase around Jupiter (see, for instance, Plainaki et al., 2013; Leblanc et al.,

209 2017). There is a widespread consensus that Jupiter's energetic ion environment provides the major

210 contribution to the generation of Ganymede's exosphere although some alternative scenarios, such

211 as secondary sputtering by ionospheric ions or water sublimation, cannot be excluded. Locally, in

212 regions near the subsolar point, where the maximum diurnal temperatures are reached (up to 152 K;

213 Orton et al., 1996) sublimated water is believed to be the dominant exosphere component. Several

214 modelling efforts have advanced our understanding of the generation of Ganymede's exosphere

215 providing important constraints for the involved processes. As in the Europa case, exospheric models

216 are based on very different approaches employing a variety of parameters and assumptions that result

217 in a large range of values for the obtained outputs. For a general description and comparison of the

218 available techniques for studying the exospheres of the Galilean satellites see the works by Marconi

219 (2007), Shematovich (2016), Plainaki et al. (2018) and references therein.

220

221 Since the role of the moon's bombardment by energetic ions is crucial for the generation of the

222 sputter-induced H_2O exosphere, significant effort has been devoted to simulating the ion circulation

223 around Ganymede and precipitation to the surface. Some of the models do provide maps of the

224 precipitation of plasma and charged energetic particles to the moon's surface as well as estimates of

225 sputtering rates. For instance, Paranicas et al. (1999) assumed that sputtering takes place in the polar

226 caps, which they defined as the surface area above the latitude of $\pm 45^0$, and they estimated a total rate

227 of $2 \cdot 10^{26}$ s^{-1}. The electric and magnetic fields determining the charged particle trajectories differ

228 among different magnetospheric models considered in literature (see, for example, Jia et al. 2009,

229 Fatemi et al. 2016, and references therein). Cooper et al. (2001) performed a back tracing technique

230 to simulate ion circulation within Ganymede's magnetosphere with only superimposed magnetic

231 fields based on Galileo data from the G2 flyby; the total sputtering rate estimated by these authors

232 was $\sim 4.3 \cdot 10^{26}$ s^{-1}.

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233 Plainaki et al. (2015) used the electric and magnetic fields from the Jia et al. (2009) global

234 Magnetohydrodynamic (MHD) model of Ganymede's magnetosphere to trace energetic charged

235 particle trajectories around the moon and to identify the regions where ions hit the ice activating

236 particle release through sputtering and radiolysis. In particular, three singly charged energetic species

237 (H^+, O^+, and S^+) at a selection of discrete energies ranging between 1 and 100 keV, were considered.

238 To absolutely normalize the flux of incident energetic particles, they used the distributions for each

239 species as determined by Paranicas et al. (1999). For each specific pair of ion composition and energy,

240 10^8 particles were simulated to ensure sufficient statistics. The total O^+ precipitating flux integrated

241 in energy in the simulation by Plainaki et al. (2015) is shown in Figure 1. The total H_2O sputtering

242 rate estimated by Plainaki et al. (2015) was $7 \cdot 10^{25}$ s^{-1}. Recently, Poppe et al. (2018) developed a

243 backwards ion tracing model to define the energetic ion population characteristics in the near-

244 Ganymede space. They used the three-dimensional, self-consistent hybrid model simulations of

245 Ganymede's magnetospheric interaction with the Jovian magnetosphere by Fatemi et al. (2016) to

246 obtain the electric and magnetic field needed for their single-particle simulations. In the simulations

247 by Poppe et al. (2018) three energetic species, H^+, O^{++}, and S^{+++}, at three discrete energies, 30 keV,

248 300 keV, and 3 MeV were considered. We note that the MHD model by Jia et al. (2009) is single-

249 fluid (O^+) whereas Fatemi et al. (2016) have implemented a hybrid plasma model (kinetic ions and

250 fluid electrons) using only the thermal component (i.e., non energetic particles). Although the

251 simulations by Plainaki et al. and Poppe et al. did not consider exactly the same inputs (e.g. ion energy

252 spectrum; magnetic field model), the results of their simulations are generally in good agreement.

253 Both studies show that there is a decrease in the ion flux from the upstream boundary at a distance of

254 ~ 2 R_G approaching the moon. Moreover, there is a shielding from the ions region on the surface

255 within the distance of ~ 2 R_G from Ganymede's center, where R_G is Ganymede's radius. The exact

256 dimension of this shielded region depends on the magnetic rigidity of the ions considered (higher

257 rigidity ions have access on the surface at lower latitudes). Enhancements in the energetic ion flux

258 downstream of Ganymede were also found by both models. Both the simulations by Plainaki et al.

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259 (2015) and Poppe et al. (2018) showed enhancements extending vertically along the upstream

260 boundaries of the Alfvén wings, however the morphologies of the flux distribution are not identical;

261 indeed, the magnetic field model considered in each case determines the details of the deceleration

262 process of the incident ion flux upon entering the Alfvén wings and the deflection of incident

263 trajectories from the near-equatorial plane to the polar regions. Over Ganymede's polar caps the flux

264 is diminished whereas downstream both simulations show evidence of trapped populations and a

265 reconnection region within Ganymede's magnetotail at distances between 2 and 4 R_G.
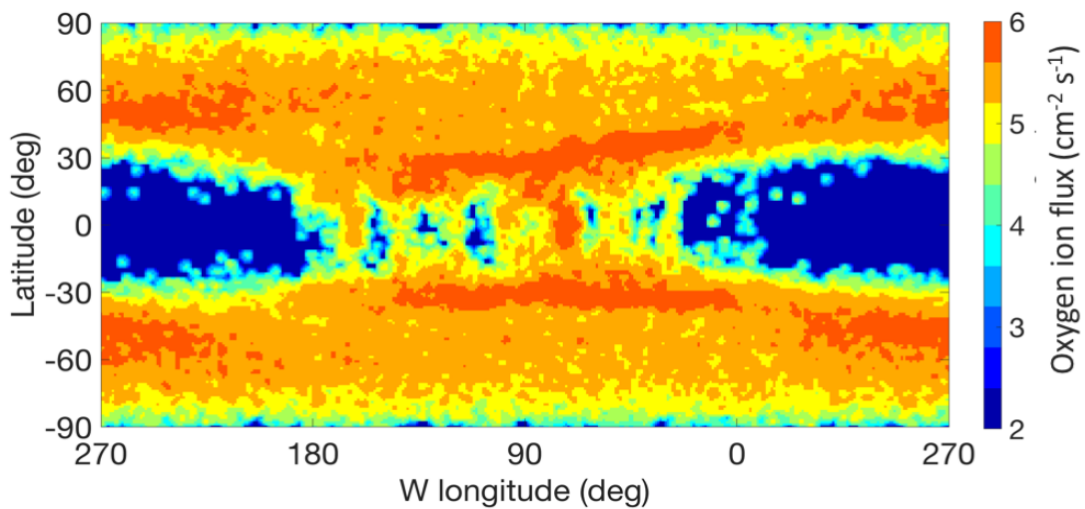
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267 **Figure 1:** Integral O^+ flux (in cm^{-2} s^{-1}) precipitating at Ganymede's surface based on simulations by

268 Plainaki et al. (2015) considering an ion energy range from 1 keV to 100 keV. In the coordinate

269 system used in this plot, the leading hemisphere apex is at longitude 90^0 and the sub-Jovian point at

270 longitude 0^0. The MHD model used for the simulations considers conditions similar to those during

271 the Galileo G8 flyby (Ganymede was near the center of Jupiter's plasma sheet).

272

273 *Exosphere models*

274 Moon exospheres have been discussed many times in the past, also through a comparative

275 planetology approach (see, for example, the collection of papers published by Coustenis et al. (2010)).

276 Our knowledge on the configuration of Ganymede's H_2O vapor exosphere is currently largely based

277 on modelling efforts. Exospheric models are in general based on very different approaches (e.g., the

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278   assumption of a collisional or a collisionless environment) and usually include H_2O and other

279   exospheric species as well.

280

281   The 2-D axisymmetric Direct Simulation Monte Carlo (DSMC) model by Marconi (2007) used a

282   multispecies approach to derive the atmospheric O_2, H_2O, H_2, and H, O, and OH spatial structure,

283   considering the non-uniform distribution of the surface temperature based on the PLS measurements

284   by Galileo. Marconi (2007) found that near the subsolar point the dominant component is H_2O vapor,

285   whereas near the polar regions the main component, at low altitudes, is molecular Oxygen; the

286   uppermost layers of the exosphere are populated by molecular hydrogen according to this model. A

287   similar approach was also followed by Shematovich (2016) who showed that collisions are

288   responsible for the observed H_2O and O_2 concentration at altitudes between 10 and 100 km from the

289   surface.

290

291   Ganymede's exosphere has been studied also through 3-D test-particle models (e.g. Turc et al., 2014;

292   Plainaki et al., 2015). Turc et al. (2014) assumed a collisionless 3-D model approach for simulating

293   Ganymede's exosphere above the sunlit trailing hemisphere. The Lyman-α emission brightness

294   obtained based on the model by Turc et al. (2014) was found much smaller than the one observed by

295   Barth et al. (1996). The modelled exosphere is clearly structured by the two particle surface sources,

296   sputtering and sublimation, resulting in a strong dichotomy between the subsolar region, where

297   sublimation takes place, and the rest of the exosphere. Far away from the subsolar region, O_2 is

298   accumulated close to the surface; instead, the lighter H_2 is found at higher altitudes, even above the

299   subsolar region.

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301   The model by Plainaki et al. (2015) was the first one to take into account the effect in the exosphere

302   generation of the ion precipitation to the moon's icy surface. This 3-D single-particle Monte Carlo

303   model was based on the previously released Europa Global model of Outgoing exospheric neutrals

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304 (EGEON, Plainaki et al. 2010;2012; 2013) as well as previous efforts for simulating Mercury's

305 exosphere (Mura et al., 2009). Plainaki et al. (2015) assumed that the main sources of Ganymede's

306 neutral environment are ion sputtering, radiolysis and water ice sublimation. The EGEON code takes

307 into account the exact angle of incidence for the ions impacting the surface. It was shown that the

308 morphology of the exosphere is significantly determined by the aforementioned processes and,

309 moreover, for the sputtered-H_2O case, there is a large difference in the concentrations of neutral

310 components between the high and low latitude regions of the exosphere. Figure 2 shows the density

311 spatial distribution of Ganymede's sputtered-H_2O exosphere according to the EGEON model.

312 Moreover, Plainaki et al. (2015) considered H_2O-sputtering yields depending on the incident ion

313 energies and therefore their exospheric model, contrary to previous ones, was based on a sputtering

314 efficiency that was spatially variable. Loss processes have also an important role in the exosphere

315 spatial distribution. Plainaki et al. (2015) incorporated in their model different plasma-induced loss

316 processes (see their table 4) among which charge exchange between low-energy charged particles

317 and exospheric molecules. Atmospheric sputtering can be an important sink for planetary and lunar

318 neutral environments, as discussed in detail by Johnson (1994), depending on the relative bulk motion

319 between plasma and neutral particles (see also discussion in Plainaki et al. (2015) and references

320 therein). In EGEON, the estimated loss rate of Ganymede's H_2O exosphere due to charge exchange

321 is of the order of ~10^{-5} s^{-1}. The importance of this process was highlighted also for the Europa case

322 in the studies by Saur et al. (1998), Dols et al. (2016) and Lucchetti et al. (2016). Plainaki et al. (2015)

323 showed that the spatial distribution of the sputtered H_2O molecules reflects the characteristics of the

324 interaction between Ganymede and Jupiter's magnetospheric particles. In particular, in the full-

325 mirroring approximation for the ion precipitation pattern, it was shown that the H_2O exosphere is

326 efficiently sputtered both in the polar region and the low latitude wake hemisphere. We note here that

327 both studies by Marconi (2007) and Plainaki et al. (2015) argue that the neutral environment is largely

328 collisionless, except for a small region near the subsolar point.

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330   Recently, Leblanc et al. (2017) studied Ganymede's neutral environment taking into account Jupiter's

331   gravitational influence and the evolution of the exosphere along the moon's orbit around the giant

332   planet. Their 3-D Monte Carlo model considered water sublimation and sputtering as the main

333   exosphere sources, and electron impact ionization and dissociation as well as particle-surface

334   interactions, as loss processes. The model follows the dynamical evolution of the exosphere as

335   Ganymede orbits Jupiter. The neutral species considered in this model were O_2, O, H_2O, H, H_2, and

336   OH released after the surface bombardment by incident Jovian ions. The model by Leblanc et al.

337   (2017) assumed that Jovian ions precipitate to the surface within the open field line regions. In

338   particular, the model considered the open-closed magnetic field lines boundary (OCFB) as derived

339   by the auroral observations described in McGrath et al. (2013). According to these authors, the

340   Ganymede exosphere appears to be highly stratified in density and composition due to the variation

341   of the ejection mechanisms and motion of the ejected molecules over the moon's orbital period. The

342   fate of the ejecta is also species-dependent due to the species dependent surface interactions. Leblanc

343   et al. (2017) confirmed the difficulty in providing a precise estimation of the water sublimation being

344   this process very sensitive in temperature variations and surface composition properties. Last, they

345   argued that the consideration of collisions among the particles in Ganymede's exosphere has a minor

346   effect in the density distribution. In Table 1 we summarize the assumptions and main findings of

347   current models of Ganymede's H_2O exosphere.

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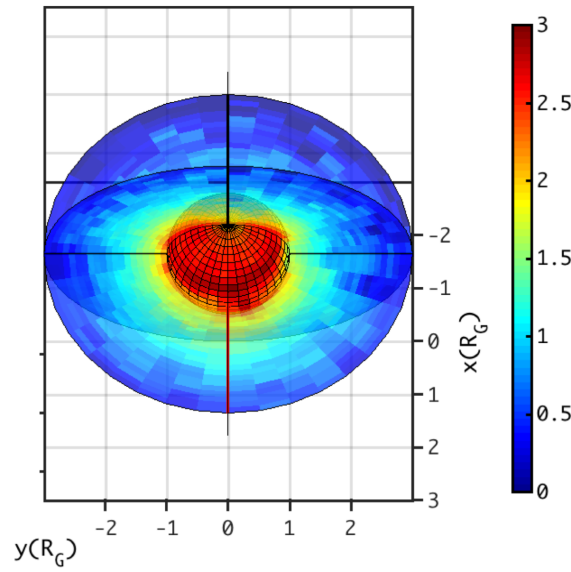
Figure 2: Density spatial distribution of Ganymede's sputtered-H_2O exosphere according to the model by Plainaki et al. (2015), as seen from the north, at a viewing angle between 0° and 90° with respect to the equator. The scale is logarithmic and density is measured in particles/cm^3. To calculate the ion surface precipitation pattern, a necessary input for EGEON, the full-mirroring approximation has been considered (for details see Plainaki et al. 2015). H_2O is efficiently sputtered in the polar regions as well as in the low latitude wake hemisphere (leading hemisphere). In the coordinate system used in this plot, the orbital direction is along the positive x axis whereas Jupiter is towards the positive y axis.

Table 1: Ganymede's H_2O exosphere: comparison of model assumptions and main findings

H_2O-exosphere model	Ion –surface interaction morphology	Technical characteristics Notes	H_2O release rate at the surface	Exosphere scale-height
Marconi (2007)	N/A	DSMC model	sputtering: 1.5×10^{26} s^{-1} sublimation: 7×10^{29} s^{-1}	70 km

15

| Shematovich (2016)	N/A	DSMC model	sputtering: 1.6×10^{26} s^{-1} (Cooper et al. 2001) sublimation: as in Marconi (2007)	80 km
Turc et al. (2014)	guided by field lines that are assumed to be closed at latitudes below $\pm 45°$ and open above the polar regions	collisionelss single-particle Monte Carlo model	sputtering: 1.5×10^{26} s^{-1} sublimation: as in Marconi (2007)	65 km
Plainaki et al. (2015)	guided by the MHD-model by Jia et al. (2009); ion circulation simulations have been performed	collisionless single-particle Monte Carlo model ion circulation simulations are used as an input for the estimation of the exosphere	sputtering: 7×10^{25} s^{-1} (estimated within the model assuming the Famà et al. (2009) yields and ion spectrum by Paranicas et al. (1999)) sublimation: as in Marconi (2007)	55 km
Leblanc et al. (2017)	taking place at the regions of the open field lines as defined by the McGrath	collisional Monte Carlo model consideration of the dynamical evolution	sputtering: 8×10^{27} s^{-1} sublimation: 8×10^{21} s^{-1} (low sublimation scenario)	~ 400 km

	et al. (2013) auroral observations	of the exosphere along the moon's orbit		

360

Figure 3 presents a comparison between the H_2O density profiles calculated by different models. We note that around the subsolar point and up to an altitude of at least ~250 km, all models have the same trend, with the exception of the model by Leblanc et al. (2017), where low sublimation rate is considered ab initio. We note that the consideration by Leblanc et al. of a low sublimation rate was motivated by the matching of the observed ratio of the H_2O column density between the leading and trailing hemispheres (Hartogh et al., 2013). All models agree that the environment is collisional only locally, i.e. near the subsolar point, assuming that the underlying surface region is mainly composed from ice. The Marconi (2007), Plainaki et al. (2015) and Turc et al. (2014) models agree that the maximum H_2O density above the subsolar surface region is of the order of 10^9 cm^{-3}, whereas for the model by Shematovich (2016) the peak density is $\sim 10^8$ cm^{-3}. Models begin to diverge substantially at higher altitudes (above ~200 km). In that region, the density of the sublimated exosphere is significantly decreased, as shown in the collisionless model by Plainaki et al. (2015) hence any diversion of a model from a strictly thermal profile is likely the result of either the assumed chemistry taking place within the exosphere or of the assumed initial energy distribution upon the particle release from the surface.

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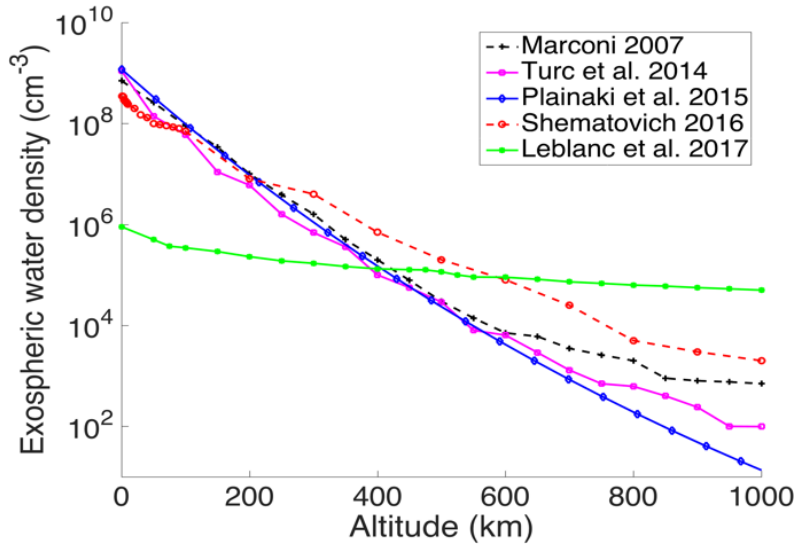
Figure 3: H_2O density profiles of Ganymede's exosphere above the subsolar point, as estimated by different models.

3. Detecting Ganymede's water vapor exosphere with JUICE/MAJIS

The ESA JUICE mission (Grasset et al., 2013), whose launch is scheduled in 2022, will explore the icy Galilean satellites thanks to a series of flybys of Callisto, Ganymede and Europa, prior to finally entering orbit around Ganymede, the mission's main target. The Ganymede dedicated orbit is divided into a high altitude (~5000 km) circular orbit phase (GCO-5000), including two elliptical orbit sub-phases, expected to last about 120 days, and a medium altitude (~500 km) circular orbit (GCO-500) phase, at least 150 days long. During periods in between flybys, observation time will be devoted also to the study of Jupiter's atmosphere, magnetosphere and auroras. The investigation of Ganymede's exosphere through the analysis of hyperspectral VIS-IR data is among the science objectives of MAJIS. In particular, MAJIS will investigate the non-LTE exospheric emissions by observing the satellite' limb at different locations and geometries, so as to assess the abundance of the exospheric component. A brief example of possible science investigations with JUICE related to

18

393 the icy satellite exospheres has been recently proposed by Plainaki et al. (2018; see paper's Section

394 4).

395

396 The MAJIS experiment onboard JUICE is led by a French-Italian consortium (Langevin et al., 2018;

397 Piccioni et al., 2014). MAJIS is a compact visible and near-infrared imaging spectrometer covering

398 the spectral range from 0.5 to 5.54 μm, split in two channels (Piccioni et al., 2019; Guerri et al., 2018).

399 The VIS-NIR spectral channel covers the 0.5-2.35 μm band with an average sampling of 3.66

400 nm/band. The IR channel works in the 2.25-5.54 μm range with a 6.51 nm/band average sampling.

401 The optical design of the MAJIS instrument relies on a f/3.2 aperture Three Mirrors Anastigmatic

402 (TMA) telescope (pupil equivalent diameter is 75 mm; focal length is 240 mm), matching two camera

403 imaging spectrometers, sharing the same entrance slit by means of a collimator. A dichroic element

404 is used to split the light beam between the two spectral channels (VIS-NIR and IR). The operative

405 temperature of the Optical Head (<140 K) and the cryogenic IR detector temperature (<90 K) are

406 achieved through passive cooling. Two detectors with similar format are foreseen for both

407 spectrometers comprising an array of 800 x 1016 pixels. Binning by 2 will always be applied in the

408 spatial direction (400 pixels). Binning by 2 is also nominal in the spectral direction (508 spectral

409 elements), leading to a 36 μm pitch, but up to 264 spectral bands can be acquired without spectral

410 binning, leading to a frame 400 pixels x 640 spectral element. The resulting Instantaneous Field of

411 View (IFOV) is 150 μrad, while the MAJIS FOV along the slit is ±1.7°. The IFOV size corresponds

412 to resolutions of 75 m/px and 300 m/px when observing respectively at nadir and at limb from a 500

413 km circular orbit around Ganymede. The instrument has a high operational flexibility thanks to a

414 series of technical capabilities. A steerable mirror in the telescope allows MAJIS to acquire

415 bidimensional hyperspectral images through consecutive scans and to compensate for the spacecraft

416 motion during the GCO-500 orbital phase or during flybys. A series of different operational modes

417 have been pre-set allowing spatial and spectral binning. Radiation noise due to charged particle

418 populations can be reduced through a despiking algorithm based on sub-frame sorting and summing,

19

419   also useful to increase the on-board data compression rate for effectively reducing the data downlink

420   volume (Langevin, 2018). Spatial and spectral binning beyond the nominal level (36 μm pitch) will

421   be implemented in order to optimize the data volume when providing extensive spatial coverage of

422   the icy satellites at medium resolution (1 to 5 km/pixel) as well as time evolution sequences for the

423   atmosphere of Jupiter and the exospheres of satellites. In Table 2, the most significant

424   characteristics of MAJIS are summarized, while more details can be found in Guerri et al. (2018) and

425   Piccioni et al. (2019).

426

427   Apart from the search for possible plumes (which will be discussed in the next section), the MAJIS

428   limb measurements are relevant to the search for H_2O exospheric emission. The most favorable

429   observing condition in this case is when the Line Of Sight (LOS) within the exosphere is totally

430   illuminated. In this case, due to effective radiative pumping, a non-LTE photon emission signal from

431   water vapor will be occurring and can in principle be strong enough to be revealed by MAJIS. In

432   particular, the MAJIS spectral range covers the H_2O non-LTE emission bands between 2.4 and 3 μm.

433   The ν_3 H_2O band at 2.67 μm is the strongest one in this spectral range and we expect to observe it

434   together with the ν_1 and ν_2 H_2O bands. Since Ganymede's exosphere is as optically thin as the

435   cometary atmospheres, we expect fluorescence to be the main excitation mechanism for the H_2O

436   bands (Crovisier, 1987; Bockelée-Morvan, 1987; Bockelée-Morvan et al., 2004). To estimate,

437   therefore, the non-LTE radiance to be measured from a spectrometer on board a spacecraft in limb

438   viewing, we follow the approach suggested by Bockelée-Morvan et al. (2015) and Villanueva et al.

439   (2012). That being the case, we are able to obtain a first simulation of the MAJIS observations of

440   Ganymede's H_2O exosphere. In this exercise, we consider currently available H_2O exosphere models

441   (see previous section) together with the instrument performance parameters. In this paper, we do not

442   perform estimations corresponding to the sublimated water density estimated by Leblanc et al. (2017).

443   The sublimation rate assumed by these authors is significantly lower than the ones considered by the

444   other models resulting in a significantly reduced Signal-to-Noise Ratio (SNR). The assumption of

20

445 such a low sublimation rate has its origin to the matching of the observed ratio of the H_2O column

446 density at the leading and trailing hemispheres (Hartogh et al., 2013), nevertheless, since the

447 methodology for deriving this quantity and the related uncertainty in the estimation are not yet clear

448 we prefer to take into account only the sublimation rate estimations available in published literature.

449 The estimations presented here are likely to be reviewed in the next years also due to theoretical

450 model updates hence the scope of this paper is to provide an indicative range for the expected

451 exospheric measurements.

452

453

454

455 **Table 2**: Basic technical characteristics of MAJIS. For a detailed description of the instrument the

456 reader is referred to Guerri et al. (2018) and Piccioni et al. (2019).

457

Basic technical characteristics of MAJIS	
Spectral range	0.5 - 5.54 μm *VIS-NIR channel:* 0.5-2.35 μm *IR channel*: 2.25-5.54 μm
Spectral sampling	*VIS-NIR channel* 3.66 nm/band *IR channel*: 6.51 nm/band
FOV along the slit	±1.7°
IFOV	150 μrad
OH operative temperature	110 - 160 K
VIS-NIR detector operative temperature	130 K (nominal)
IR detector operative temperature	90 K (nominal)

458

459

21

To estimate the expected non-LTE radiance we extract the line parameters from the HITRAN database (Gordon et al., 2017) and we compute the cross-sections σ (in cm^2) for the roto-vibrational lines of the v_1, v_2 and v_3 H$_2$O band. We assume band emission rates (g-factors), gf, equal to 3.349 × 10^{-4} s^{-1}, 3.33×10^{-5} s^{-1} and 2.67×10^{-4} s^{-1} for the H$_2$O v_3, v_1 and v_2 bands, respectively (Villanueva et al., 2012). Since the aforementioned values refer to at the heliocentric distance of 1 AU, their rescaling to 5.2 AU, is required.

The band integrated radiance (in W m^{-2} sr^{-1}) can be estimated as follows:

$$I_{i,l} = \frac{(h \cdot \underline{v})}{(4 \cdot \pi)} \cdot gf_i \cdot N_l \tag{1}$$

where $\underline{v}$ is the central frequency of the band, h is the Planck constant, N_l (in m^{-2}) is the column density along the LOS inside the l exospheric level. The i index characterizes the H$_2$O spectroscopic transition. Since the band integrated radiance can be also written as

$$I_{i,l} = f_{i,l} \cdot \int \sigma_{i,l}(v) dv \tag{2}$$

where $f_{i,l}$ is a conversion parameter (in W cm^{-4} cm sr^{-1}), based on Eq.s (1) and (2), the emitted radiance $R_{i,l}$ (in W m^{-2} cm sr^{-1}) along the LOS inside the l exospheric level and for the i transition can be written as

$$R_{i,l}(v) = f_{i,l} \cdot \sigma_{i,l}(v) = \frac{h \cdot v \cdot gf_i \cdot N_l}{4 \cdot \pi \cdot \int \sigma_{i,l}(v) dv} \cdot 10^4 \tag{3}$$

Considering all the spectroscopic transitions and exospheric levels occurring along the LOS, the radiance at the detector is:

$$R(v) = \sum_i \sum_l R_{i,l}(v) \tag{4}$$

The radiance R computed so far has a very high spectral resolution equal to 2x10^{-3} cm^{-1} chosen as the best compromise between the inclusion of the spectroscopic lines and the required computational time. We then convolve R with the MAJIS IR channel instrumental line shape expected to follow a

22

Gaussian profile with a conservative Full-Width-Half-Maximum FWHM estimated at 12.98 nm

484 corresponding to a factor of two times the spectral sampling of 6.49 nm (Guerri et al., 2018).

485

486 During Ganymede flybys as well as in Ganymede orbits, all exosphere observations are planned with

487 the slit oriented parallel to the limb. This is the best configuration as the whole slit would be exposed

488 to the maximum exosphere signal while reducing possible straylight from the surface, and the

489 sensitivity of the measurement to the tangent altitude would be maximum as well. In Figure 4 we

490 show the geometry of a hypothetical observation taking place at UTC 2032-09-15 T09:42:42, with

491 JUICE being distant ~7700 km from the center of Ganymede (altitude of 5100 km), with a spatial

492 resolution of ~ 0.75 km at the sub-spacecraft point and ~ 1 km in terms of altitude resolution of the

493 exosphere at the limb.
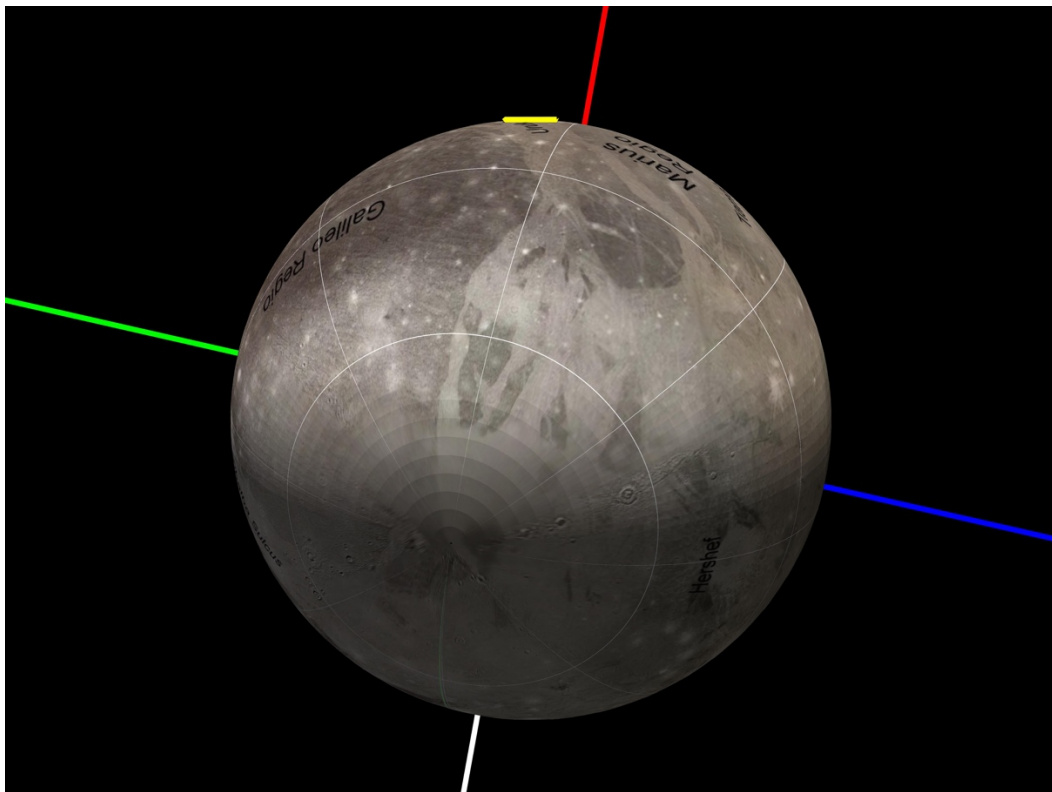
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495

496 **Figure 4:** Observation of Ganymede exosphere on 2032-09-15 T09:42:42 in CREMA 3.0 with limb

497 pointing by MAJIS and the MAJIS slit oriented parallel to the limb. MAJIS FoV is the yellow

23

segment. Colored lines indicate directions towards Jupiter (white), anti-Jupiter (red), leading (green) and trailing hemisphere (blue). This attitude is a preliminary estimation: technical constraints such as solar illumination on panels are still to be evaluated.

Most exospheric observations during Ganymede flybys will be made at relatively large distances (e.g., 40000 km corresponding to a spatial resolution of 6 km/px) as closer observations conflict with remote sensing and geophysics observations of Ganymede. The most favorable phase for Ganymede exospheric observations is the near circular phase of GCO-5000 (120 days-long) and the two adjacent elliptical phases (2 x 15 days) as all latitudes can be observed in the optimum geometry (limb pointing with the MAJIS slit parallel to the limb) on orbital segments extending from the night side up to the pole. In this case pointing can be driven by exospheric observations whereas most remote sensing observations of the surface will be made on the day side of the GCO-5000 orbit. When the spacecraft is at an altitude of ~ 5000 km the spatial resolution when pointing at the limb is 1.07 km/px. The dwell time is ~ 1 s as the orbital velocity is 1.1 km/s. Such integration times lead to relatively low SNR. SNR can be improved by extending the repetition time at the expense of vertical spatial resolution. As the MAJIS slit is tangent to the limb, one can co-add spatial pixels without degrading the vertical spatial resolution at the center of the slit (closest to the limb). Since the co-adding technique involves only adjacent bins along the slit, which is oriented tangent to the limb, the worst binned spatial resolution is ~17 km/px. We note that the considered exospheric model has a horizontal spatial resolution of about $1/10 \; R_G$, which is much higher than the worst spatial resolution we can have along the slit. Therefore, we can assume our exospheric conditions as homogeneous within the co-added bin. Moreover, during the other planned JUICE orbital phases around Ganymede (e.g., GCO-500), the distance of the spacecraft from the target will be lower than the one we considered here and this will further improve the MAJIS spatial resolution with respect to the fixed horizontal spatial resolution of current exospheric models.

24

The noise level is estimated using the MAJIS radiometric model, taking into account the repetition time and the despiking strategy (sub-integration time and number of selected sub-integrations after sorting). An example of the signal we expect to measure between 2.4 and 3 µm (the spectroscopic range with stronger H_2O line intensities) is shown in Figure 5. These simulations, based on the Plainaki et al. (2015) model extended in altitude up to 1000 km, are performed at a tangent latitude of ~10°N, assuming the LOS within the exosphere totally illuminated. For completeness, we also estimated the SNR corresponding to the exospheric models of Marconi (2007; Figure A1), Shematovich et al. (2016; Figure A2), and Turc et al. (2014; Figure A3) which are presented in the appendix.

Two representative observation cases have been considered for observations from GCO-5000:

- High vertical resolution: 1.1 s repetition time, binning x 4 along the slit (projected IFOV: 1.1 km vertical, 4.3 km along slit); despiking strategy: lowest of 3 CDS with 0.1 s integration time.

- Low vertical resolution: 9 s repetition time, binning x 16 along the slit (projected IFOV: 10 km vertical, 17 km along slit); despiking strategy: average of 3 lowest CDS out of 6 with 0.643 s integration time.
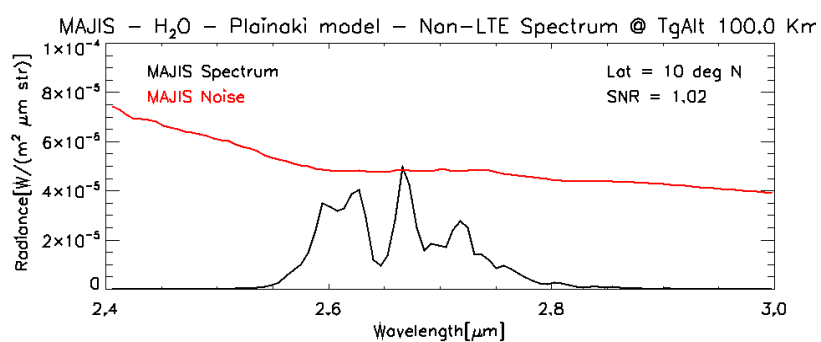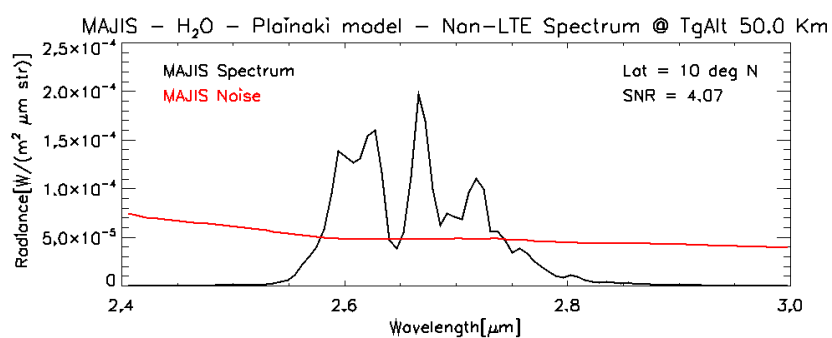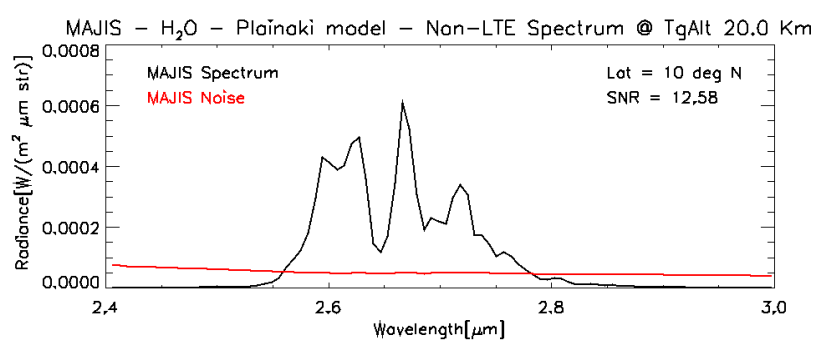
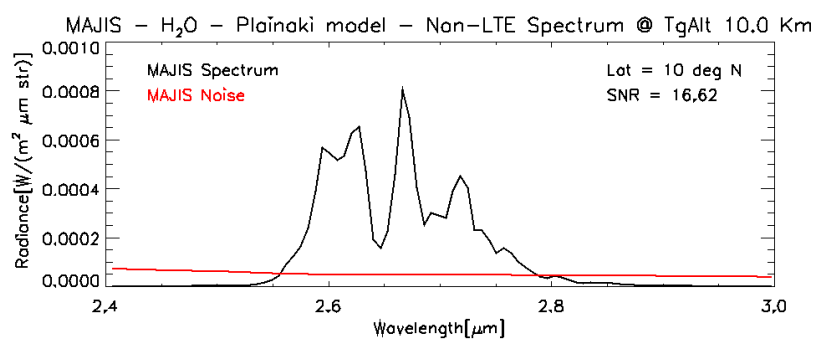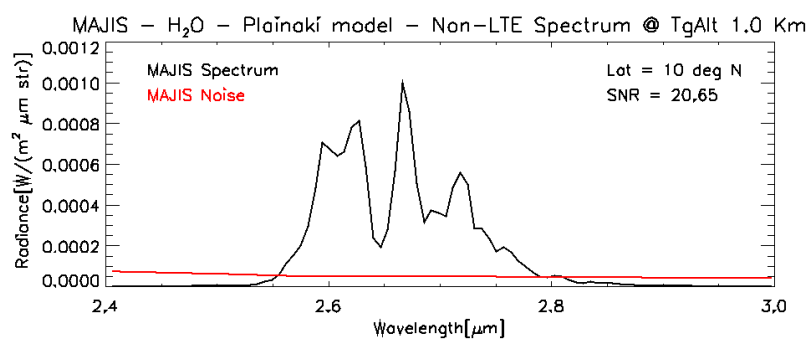The estimated SNR at peak intensities have been evaluated in Table 3 for both observational modes at latitude ~10°N and three tangent altitudes (10 km, 50 km and 100 km). Such observations will provide constraints on actual H_2O column densities as a function of altitude, making it possible to adjust the observation strategy for exospheres once in Ganymede orbit.

Table 3: Observing the water exosphere of Ganymede with MAJIS. The Signal-to-Noise Ratio (SNR) has been evaluated for high vertical resolution observations (spatial resolution 4.3 km along slit x 1.1 km vertical) and low vertical resolution (17 km along slit x 10 km vertical) as a function of the tangent altitude for different H_2O exospheric models.

25

Model	Tangent altitude (km)	MAJIS SNR (high vertical res.)	MAJIS SNR (low vertical res.)
Marconi (2007)	10	12.6	178
Marconi (2007)	50	5.62	79.2
Marconi (2007)	100	1.98	27.8
Plainaki et al. (2015)	10	16.6	234
Plainaki et al. (2015)	50	4.07	57.2
Plainaki et al. (2015)	100	1.03	14.4
Shematovich (2016)	10	4.82	67.9
Shematovich (2016)	50	2.73	38.5
Shematovich (2016)	100	1.94	27.3
Turc et al. (2014)	10	16.0	225.8
Turc et al. (2014)	50	3.08	43.3
Turc et al. (2014)	100	1.22	17.1

549 Figure 6 shows the estimated SNR as a function of wavelength for high vertical resolution with

550 different exosphere models. Our simulations using the models by Marconi (2007), Plainaki et al.

551 (2015), Shematovich (2016), and Turc et al. (2014), indicate that MAJIS provides outstanding

552 capabilities for observing water in Ganymede's exosphere in limb observations at tangent altitudes

553 below 100 km from the surface and at latitudes $\pm$ 10°. The upcoming measurements with JUICE of

554 Ganymede's exosphere are therefore expected to represent a significant test for the currently available

555 exospheric models providing at the same time important feedback for developing more

556 comprehensive scenarios.

MAJIS − H₂O − Plaïnaki model − Non−LTE Spectrum @ TgAlt 1.0 Km

557

MAJIS − H₂O − Plaïnaki model − Non−LTE Spectrum @ TgAlt 10.0 Km

558

MAJIS − H₂O − Plaïnaki model − Non−LTE Spectrum @ TgAlt 20.0 Km

559

MAJIS − H₂O − Plaïnaki model − Non−LTE Spectrum @ TgAlt 50.0 Km

560

MAJIS − H₂O − Plaïnaki model − Non−LTE Spectrum @ TgAlt 100.0 Km

561

27

562 **Figure 5:** Simulated MAJIS spectrum (black line, IR channel, nominal detector temperature = 90 K)

563 of the H_2O Non-LTE emission between 2.4 and 3 microns for the Ganymede exosphere model by

564 Plainaki et al. (2015) at lat~10°N and tangent altitudes of 1, 10, 20, 50, and 100 km. Red line indicates

565 the predicted Noise Equivalent Spectral Radiance (NESR) of the MAJIS instrument for high vertical

566 resolution observations.

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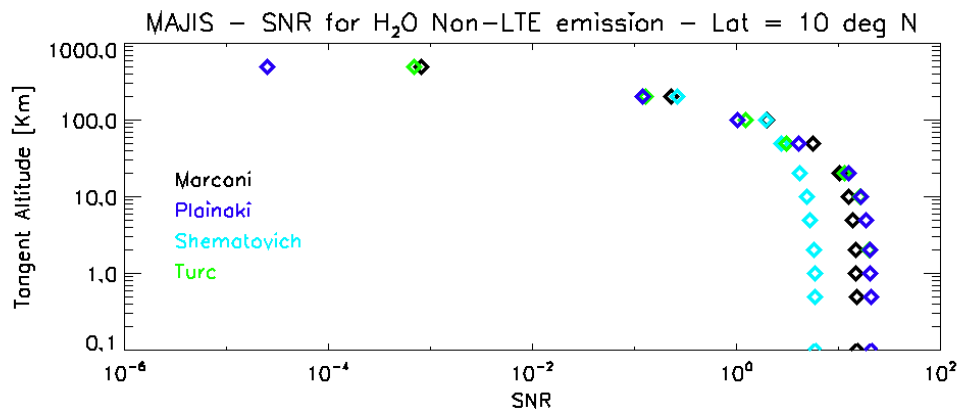
568

569 **Figure 6:** Comparison of the MAJIS signal-to-noise ratios for H_2O non-LTE emission for high

570 vertical resolution observations computed for different exospheric models as a function of

571 observation tangent altitude at latitude ~10°N. See text for details.

572

573 Several parameters related to the water deposition on the surface (e.g., the spatial distribution of the

574 H_2O abundance on Ganymede's surface, the albedo map) are expected to be linked to the impact of

575 the external environment. Recently, studies based on VLT/SINFONI data (1.40–2.50 μm) showed

576 that the abundance maps of H_2O-ice on Ganymede's surface are characterized by a latitudinal gradient

577 linked to the magnetosphere ion bombardment (Ligier et al. 2019). Prior to this study, Khurana et al.

578 (2007) had shown that there is a good correlation between the position of the OCFB and the boundary

579 of Ganymede's polar cap, suggesting that this is evidence of the effect of charged particles impacting

580 the moon's surface. Khurana et al. (2007) suggested also that the equatorial leading/trailing

581 asymmetry was due to the preferential flux of ions. Sputtering can remove part of the surface upper

582 layers allowing the underlying fresh ice to emerge and be subsequently released in the exosphere. So,

28

583 the related redistribution of water frost on the surface (due to sputtering and also water deposition

584 from the exosphere) is expected to cause a surface brightening that is well correlated with the ion

585 precipitation patterns and the sputtered-H_2O water exosphere. Moreover, radiation can also have an

586 impact on the structure of surface water ice: indeed, the existence of amorphous ice –mostly in the

587 first micrometer layers is due to higher radiation processing (Hansen and McCord, 2004; 720 Famà

588 et al. 2010). Therefore, observing with MAJIS the surface regions that are expected to be mostly

589 bombarded by Jupiter's magnetospheric ions should provide also an indication of the expected water

590 deposition from the exosphere itself. Moreover, almost simultaneous observations of Ganymede's

591 exosphere and surface with MAJIS could allow to infer about the link between them in terms of water

592 deposition, especially if performed at different locations.

593

594 **4. Possible detectability of Ganymede's plumes**

595

596 Currently, there is no empirical evidence for the presence of plumes at Ganymede. However, lessons

597 learned from both Enceladus, where active plumes have been imaged by the ISS camera and the

598 VIMS spectrometer on board the Cassini spacecraft (Porco et al., 2006; Hedman, 2009), and Europa

599 (Roth et al., 2014; Sparks et al., 2016; Jia et al., 2018; Paganini et al., 2019), provide a good

600 motivation for estimating the plume detection capability at Ganymede by the instruments on board

601 JUICE.

602

603 In principle, MAJIS (as the JANUS camera) can detect plumes through the scattering of solar light

604 by plume grains. In the range of grain size inferred at Enceladus (radii of about 2-5 μm), the scattering

605 efficiency is strongly peaked in the forward direction, making the detection of plumes much more

606 likely in high solar phase angle configurations. Therefore, optimal conditions for plume detection

607 with MAJIS are the limb viewings at high phase angle and with a spatial resolution high enough to

608 resolve the plume in its vertical extension. In both Enceladus and Europa cases, plume heights have

29

609 been estimated to be of the order of 100-200 km (e.g., Roth et al., 2014) and this scale length is

610 assumed as an upper limit on Ganymede.

611

612 On the basis of the currently planned trajectories of spacecraft, the above mentioned observing

613 constraints are expected to be achieved several times along the JUICE mission, during Ganymede

614 flybys as well as during the Ganymede orbital phase. The different opportunities mainly differ in the

615 observing range, varying from $2 \cdot 10^5$ km to 4000 km, yielding large variations of spatial resolution.

616 We show here the evaluation of the detection limits on the plume density in three different

617 configurations of MAJIS observations, taken as study cases: (a) a distant flyby, (b) a close flyby, and

618 (c) a high orbit (GCO-5000). We point out that currently only case (c) is compatible with Sun

619 avoidance rules except when JUICE is in the shadow of Jupiter (and Ganymede is not), nevertheless,

620 with the scope to present better our methodology within the current paper, we speculate on all three

621 hypothetical cases.

622

623 In all cases, plume scattering properties are calculated using the Mie theory for spherical

624 homogeneous particles (Bohren and Huffman, 1983), assuming a pure water ice composition, and

625 grain sizes lognormally distributed with a 3 μm effective radius and a 1.5 effective variance. The

626 solar radiance scattered by the plume is evaluated in a single scattering approximation as

$$I_{pl}(\lambda) = \frac{1}{4\pi} F_{sun}(\lambda) \underline{C_{sca}}(\lambda) \underline{P}(\lambda, \alpha) N_{pl} f_f \tag{5}$$

628

629 being $F_{sun}(\lambda)$ the solar radiance at the actual heliocentric range, $\underline{C_{sca}}(\lambda)$ and $\underline{P}(\lambda, \alpha)$ respectively the

630 single scattering cross section and single scattering phase function of the plume particles, averaged

631 over their size distribution, N_{pl} the plume number column density, and f_f the filling factor of the

632 MAJIS pixel. The latter is computed as the fraction of the MAJIS instantaneous field-of-view

633 intersecting a cylindrical homogeneous plume, 200 km in height and 10 km in diameter. With this

30

634 assumption the filling factor equals unity for observing distances less than about 65000 km. Plume

635 particles thermal emission intensity is estimated below 1% of the solar scattered radiation levels for

636 wavelengths shortward of 5 μm (assuming a 120 K grain temperature), and is therefore neglected.

637 Expected noise levels for plume observations, taking into account the source, background, and dark

638 current noise sources assuming a detector temperature of 130 K for the MAJIS VIS-NIR channel (see

639 Table 2), are evaluated as a function of the plume column density (in the line-of-sight direction) and

640 exposure times. The resulting SNR appears higher in the 0.8-1.0 μm wavelength range, and the

641 average SNR value in that range is used to define plume detection limits.

642

643 The results for the three study cases here considered are shown in Figure 7, for a range of MAJIS

644 exposure times (no despiking processing included) and plume column densities, while the

645 corresponding observing parameters are summarized in Table 4. The red, orange, and green thick

646 lines indicate the column density detectable with a SNR level of 1, 2, or 3 respectively. For

647 comparison, the range of plume densities estimated for the Enceladus case (Porco et al., 2006) are

648 indicated by the blue-filled region.

649 Our analysis shows that the b) case (close flyby) is the most favorable one, since the simultaneous

650 optimization of both resolution and phase angle enables the detection of low density plumes, 1-2

651 orders of magnitudes thinner than Enceladus ones, even with short integration times. In the a) case

652 (distant flyby) the increase of observing distance pertaining to high phase angles makes the plume

653 subpixel, and detection of thin features requires integration times longer than about 10 sec. The c)

654 case (high-altitude orbit phase) appears the worst one, since even the detection of a high-density

655 (Enceladus-like) plume requires very long integration times. It is interesting to note that the lower

656 detection probability in the c) case is due to the smaller phase angle achievable in the orbit phase,

657 which are predicted to not overcome the 140° value. A better performance may be achieved in this

658 phase if the plume contains a significant population of submicron grains, whose forward scattering

659 peak is less pronounced.

31

660 It is worth stressing that these estimations are based on the currently available radiometric model of

661 the instrumental response, while more quantitative predictions require the actual instrumental

662 response which will be measured after the integration of the MAJIS flight-model.

663

Table 4: Detectability of Ganymede plumes: parameters used for detection limits

estimations for the three hypothetical study cases

Study case	S/c distance	Solar phase angle	Heliocentric distance	Spatial resolution	Filling factor for MAJIS pixel
a) distant flyby case (Dec. 2030)	189000 km	174°	5.33 AU	28 km/pixel	0.35
b) close flyby case (Sep. 2030)	4500 km	175°	5.37 AU	0.7 km/pixel	1.0
c) high orbit case (Nov. 2032)	7700 km	135°	5.10 AU	1.2 km/pixel	1.0

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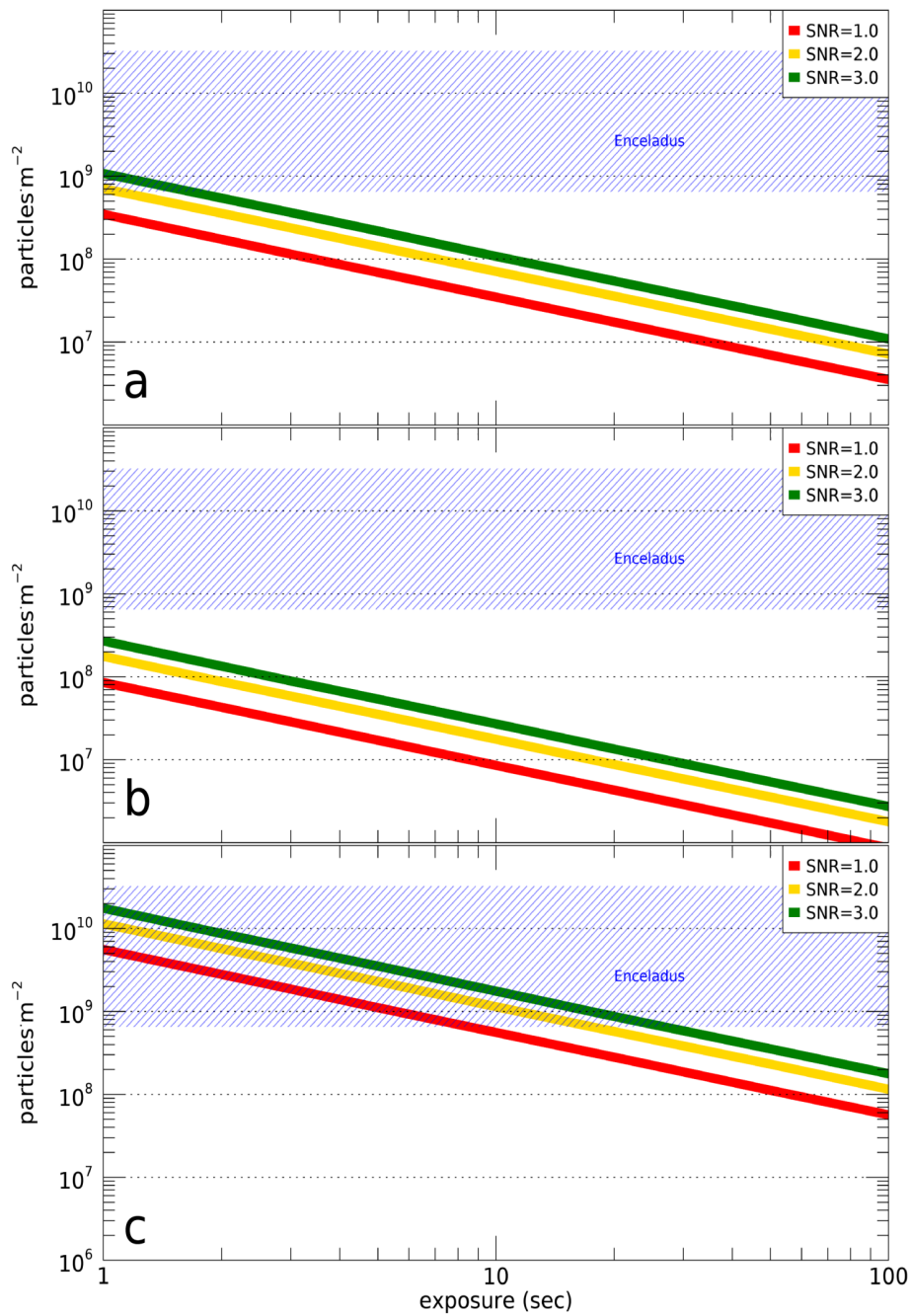
Figure 7: Detectability of a water ice plume in the three different study cases described in text and Table 4 and representing conditions encountered during different JUICE mission phases: distant flyby (panel a), close flyby (panel b), high orbit (panel c). Red, orange, and green lines indicate the plume column density detectable with SNR values of 1, 2, or 3, respectively (as average value in the 0.8-1.0 μm range). The blue-filled regions show the range of densities of the Enceladus plume. The despiking process has not been taken into account.

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5. **Discussion and Conclusions**

Lunar exospheres are important sources of neutral gas in the outer Solar System often associated with the formation of torus-shaped clouds (e.g., Mauk et al., 2003; Shematovich, 2016). They play an important role in the balance between the neutral gas and magnetospheric plasma in the giant planetary systems. The determination of the properties of the exospheric environment provides the necessary information to better understand the weathering processes induced on ice by the radiation environment.

Surface sputtering and water sublimation play a key role in the generation and dynamical evolution of Ganymede's exosphere. In general, numerical models simulating the generation of Ganymede's surface-bounded H_2O exosphere agree that thermal ion populations provide a minor contribution to the total sputtering rate with respect to heavy energetic ions (e.g., Sulfur ions and Oxygen ions). Water sublimation is expected to be the dominant surface release process only locally, although some uncertainty in the considered rates exists due to the lack of quantitative information on the surface impurities concentration and actual temperature. For comparison, on Saturn's moon Tethys the intense bombardment of high-energy magnetospheric electrons collimated on the leading hemisphere of the moon is the driving mechanism causing the formation of the equatorial lens and nearby "Pacman" feature (Howett, 2012). As a consequence of the electrons bombardment, the ice grains displaced on the regolith are sinthered together (Filacchione et al., 2018), forming larger grains and causing local thermophysical anomalies: the lens appears in fact colder (Howett et al., 2012; Filacchione et al., 2016) and darker (Schenk et al., 2011; Filacchione et al., 2018) with respect to nearby regions not altered by the electron flux. Exospheric models for Ganymede (e.g., Marconi 2007; Turc et al., 2014; Plainaki et al., 2015; Shematovich 2016; Leblanc et al., 2017) generally almost agree in terms of water release rate from the surface and maximum H_2O vapor density, however, the different assumptions in each model result in different density profiles. Future

experimental work in estimating ice sputtering and radiolysis yields and even more accurate estimations of the exosphere sources (e.g., through the consideration of the entire energy range of the impinging ions) and loss rates (e.g., through the definition of the precise morphology of the plasma around Ganymede) will certainly help to better estimate the vapor H_2O density distribution.

In this work, we provided a first evaluation of the potential of observing Ganymede's H_2O exosphere with JUICE/MAJIS. Our main motivation for this exercise was the possibility to obtain IR radiation measurements that will constrain the efficiency and morphology of the surface particle release as well as the energy exchange between the Jovian system and the moon. Two representative observation cases have been considered for observations from GCO-5000, one at high vertical resolution (projected IFOV of ~1.1 km) and one at low vertical resolution (projected IFOV of ~10 km). The results of our estimations provide evidence that given the specifications of MAJIS, the instrument has the necessary sensitivity to observe the moon's water vapor environment with a SNR higher than 1 during limb observations with tangent altitude below 100 km from the surface and at latitudes $\pm 10°$, even when considering the model leading to the lowest column densities of water vapor. If current exospheric models are correct, and in absence of plumes, we confirm that the H_2O exosphere to be detected with MAJIS will be the one generated through water ice sublimation, since the SNR corresponding to the sputtered water component is expected to be extremely low. Even if this were the case, the possible investigation of Ganymede's exosphere with MAJIS is still important since it can provide useful information for speculating on the surface weathering processes. We note that the deposition of neutral species from the exosphere onto the moon's surface can spectrally mask the weathering products or directly start new chemical patterns. Therefore, to understand the processes of weathering we need first to characterize the moon's exosphere, even if only locally. Based on the above, the most favorable observation condition during JUICE is the one focused on the region around the subsolar point. For limb observations, MAJIS would require setting its slit tangent to the limb, a configuration that avoids saturation from the satellite if the limb is sunlit, providing at the

same time optimum vertical resolution with spatial binning. Potential joint-observations between MAJIS and UVS are likely to increase the scientific return from the observation of Ganymede's exosphere. We note here that the estimations in the current paper are likely to be revised in the next years also due to theoretical model updates hence our results provide a first indicative range for the expected exospheric measurements. The upcoming measurements with JUICE will provide proof of the most realistic scenario among the ones currently proposed for the exosphere of Ganymede.

Considering the potential detection of plumes at Ganymede (if any), we showed that particular combination of resolution and phase angle shall enable to optimize the MAJIS observation and resulting SNR of low density plumes. The simulation indicates that MAJIS can detect plumes of density 1-2 orders of magnitudes thinner than the Enceladus ones by optimizing the integration times and selecting the VISNIR channel. Further detailed work in this direction is strongly required to take into consideration the expected properties of a potential plume at Ganymede (considering also the role of the moon's orbit phase around Jupiter), as well as the real performances of the instrument after characterization, the validation of the despiking algorithm once in flight, and (during Ganymede encounters), the compatibility between the necessary (for the observations) phase angles and the Sun avoidance rules requested by MAJIS. Potential planning for a series of observations at different latitudes together with JANUS, as done in the past for Enceladus by ISS and VIMS onboard Cassini (Hedman et al., 2009) will help us to better understand the properties of plumes (if any) and, possibly, their variability in time. Future work in this direction is intended.

There are some drawbacks related to the estimations presented in this paper. First, the current study considers as inputs the outputs of numerical simulations hence the differences among the obtained calculations cannot be neither rigorously nor easily attributed to specific parameters within each model. Different theoretical models of the H_2O exosphere, and different configurations between Ganymede, Jupiter and the Sun may result in different exosphere morphologies (see, for example,

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Leblanc et al., 2017) hence this study provides only a preliminary and rough estimation of the expected measurement by MAJIS. Indeed, Ganymede's magnetosphere changes continuously due to the moon's motion above and below the Jupiter plasma sheet but also due to the variation of the plasma sheet properties itself. Recently, Vogt et al. (2017) found that Jupiter's current sheet current density parameter varies by ~15–20% with respect to its average value. The exosphere is expected to be influenced by such changes in terms of both generation and loss process efficiency. The study of the variation of the exosphere due to variations of the space environment external to Ganymede (planetary space weather) is an important requisite for future estimations of its detectability and for optimizing the observational conditions. Second, all the exospheric models considered in this study assume that the H_2O sublimation rate above the subsolar point is relatively high. Unfortunately, there are currently no published observational evidences that prove (or deny) this fact. At a larger perspective, future exploration of the Outer Solar System requires knowledge on the planetary space weather conditions near and within the system under investigation (for a more detailed discussion in this context see Plainaki et al. (2016) and references therein). Last, our estimations show that the dominant component to be observed with MAJIS is likely sublimated H_2O, for which all models estimate the same maximum concentration. Although the sputtered H_2O exosphere, as estimated nowadays by models, is likely under the detectability limits of MAJIS, the remote possibility of its observation should not be ruled out. This is because ongoing laboratory work on the efficiency of H_2O release from ice as well as recent estimations of updated release yields (see, for instance, Teolis et al. 2017) and of the role of the radiation environment (see, for instance, Poppe et al. 2018) and secondary sputtering (Carnielli et al., 2019) may result in an increase of the H_2O density. In such a case, the current estimations provide only a lower limit for future detection.

To accurately estimate the SNR expected for MAJIS during limb observations of Ganymede's H_2O exosphere, further detailed work is required, taking also into consideration further opportunities to observe the exosphere of Ganymede. The current study, therefore, will be expanded and the results

772 will be integrated considering different observational opportunities during the JUICE mission. In

773 particular, we plan to integrate in our radiance simulator the actual MAJIS observational geometries

774 (incidence and emission angles, tangent altitudes, spacecraft distances, etc.) based on the

775 Consolidated Report on Mission Analysis (CReMA; Boutonnet and Schoenmaekers, 2012)

776 trajectories and the instrument pointing abilities. Such an approach will provide feedback for driving

777 the MAJIS observational planning in order to optimize the Ganymede's exosphere detection

778 accordingly with the MAJIS spectral sensitivity.

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APPENDIX

953   **Figure A1:** Simulated MAJIS spectrum (black line) of the H_2O Non-LTE emission between 2.4 and 3 μm for

954   Ganymede's exosphere model by Marconi et al. (2007) at lat~10°N and tangent altitudes of 1, 10, 20, 50, 100

955   km above the surface, from top to bottom panel respectively. Red line indicates the predicted Noise Equivalent

956   Spectral Radiance (NESR) of the MAJIS instrument for high vertical resolution observations.

957   **Figure A2:** Simulated MAJIS spectrum (black line) of the H_2O Non-LTE emission between 2.4 and 3 μm for

958   Ganymede's exosphere model by Shematovich et al. (2016) at lat~10°N and tangent altitudes of 1, 10, 20, 50,

959   100 km above the surface, from top to bottom panel respectively. Red line indicates the predicted Noise

960   Equivalent Spectral Radiance (NESR) of the MAJIS instrument for high vertical resolution observations.

961   **Figure A3:** Simulated MAJIS spectrum (black line) of the H_2O Non-LTE emission between 2.4 and 3 μm for

962   Ganymede's exosphere model by Turc et al. (2014) at lat~10°N and tangent altitudes of 1, 10, 20, 50, 100 km

963   above the surface, from top to bottom panel respectively. Red line indicates the predicted Noise Equivalent

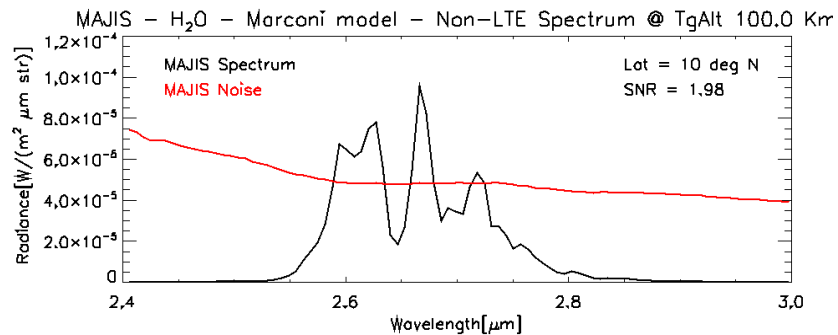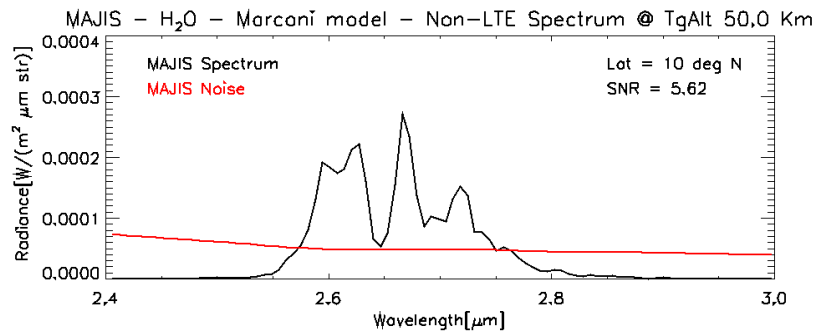964   Spectral Radiance (NESR) of the MAJIS instrument for high vertical resolution observations.

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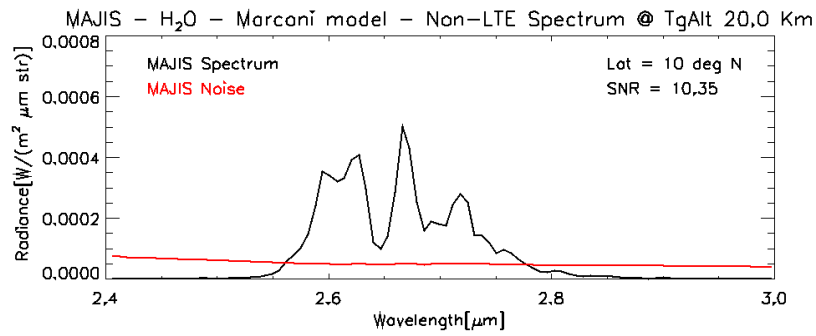
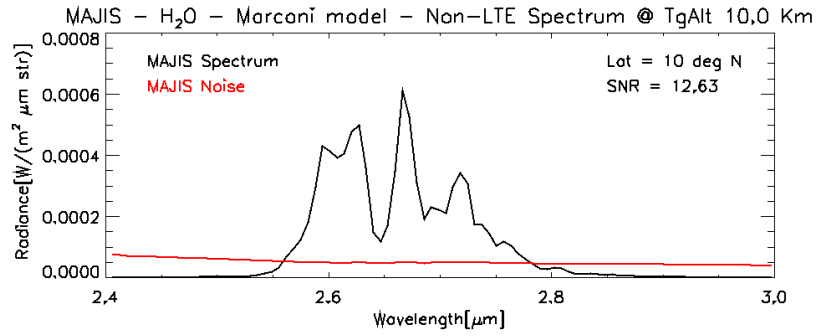966

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Figure A1

MAJIS – H₂O – Marconi model – Non-LTE Spectrum @ TgAlt 1,0 Km

MAJIS Spectrum
MAJIS Noise
Lat = 10 deg N
SNR = 14,89

978

MAJIS – H₂O – Marconi model – Non-LTE Spectrum @ TgAlt 10,0 Km

MAJIS Spectrum
MAJIS Noise
Lat = 10 deg N
SNR = 12,63

979

MAJIS – H₂O – Marconi model – Non-LTE Spectrum @ TgAlt 20,0 Km

MAJIS Spectrum
MAJIS Noise
Lat = 10 deg N
SNR = 10,35

980

MAJIS – H₂O – Marconi model – Non-LTE Spectrum @ TgAlt 50,0 Km

MAJIS Spectrum
MAJIS Noise
Lat = 10 deg N
SNR = 5,62

981

MAJIS – H₂O – Marconi model – Non-LTE Spectrum @ TgAlt 100,0 Km

MAJIS Spectrum
MAJIS Noise
Lat = 10 deg N
SNR = 1,98

982

46

Figure A2

MAJIS – H$_2$O – Shematovich model – Non–LTE Spectrum @ TgAlt 1.0 K

MAJIS Spectrum
MAJIS Noise

Lat = 10 deg N
SNR = 5.82

983

MAJIS – H$_2$O – Shematovich model – Non–LTE Spectrum @ TgAlt 10.0 K

MAJIS Spectrum
MAJIS Noise

Lat = 10 deg N
SNR = 4.84

984

MAJIS – H$_2$O – Shematovich model – Non–LTE Spectrum @ TgAlt 20.0 K

MAJIS Spectrum
MAJIS Noise

Lat = 10 deg N
SNR = 4.14

985

MAJIS – H$_2$O – Shematovich model – Non–LTE Spectrum @ TgAlt 50.0 K

MAJIS Spectrum
MAJIS Noise

Lat = 10 deg N
SNR = 2.73

986

MAJIS – H$_2$O – Shematovich model – Non–LTE Spectrum @ TgAlt 100.0 I

MAJIS Spectrum
MAJIS Noise

Lat = 10 deg N
SNR = 1.93

987

47

Figure A3

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