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Ganymede's Ionosphere observed by a Dual-Frequency Radio Occultation with Juno

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Key Points:

- A dual-frequency radio occultation experiment of Ganymede's ionosphere was conducted with the Juno spacecraft on June 7, 2021
- Ingress observed an ionosphere with peak density 2000 ± 500 ($1-\sigma$) cm^{-3} but no statistically significant signature was detected on egress
- Ingress detection occurred in the open field line region, where higher electron impact ionization rates may increase the electron density

24 **Abstract**

25 In June 2021, the Juno spacecraft executed a close flyby of Ganymede. During the encounter, Juno
26 passed behind Ganymede for 15 minutes as observed from Earth, providing the geometry to
27 conduct a radio occultation experiment to probe Ganymede's tenuous ionosphere. X-band and Ka-
28 band radio links were transmitted from Juno to antennas at the Deep Space Network. Electrons
29 encountered along the radio propagation path advance the signal's phase and a linear combination
30 the two frequencies allows for a direct measurement of the electron content along the propagation
31 path. On occultation ingress, an ionosphere peak of 2000 ± 500 ($1-\sigma$) cm^{-3} near the surface was
32 observed. On occultation egress, no statistically significant ionosphere was detected. Ingress
33 observation viewed where Ganymede's intrinsic magnetic field lines are open whereas egress
34 observation viewed where the field lines are closed, implying electron impact ionization plays a
35 key role in the generation of the ionosphere.

36

37 **Plain Language Summary**

38 Juno conducted a flyby of Ganymede, the largest Galilean moon of Jupiter, on June 7, 2021. During
39 the flyby, the Juno spacecraft set behind Ganymede as observed by the Earth. Juno's radio signals
40 were captured by the Deep Space Network during this time to make radio occultation
41 measurements of Ganymede's ionosphere. Elevated electron density was measured on occultation
42 ingress but no statistically significant ionosphere was detected on egress. These results are
43 consistent with Galileo's radio occultation observations and provide insight into the generation
44 mechanisms of Ganymede's ionosphere.

45 **1 Introduction**

46 The Galilean moons of Jupiter are known to have atmospheres and ionospheres, detected
47 with both ground-based observations and spacecraft data. An oxygen-hydrogen atmosphere was
48 discovered on Ganymede with observations by the Hubble Space Telescope (Hall et al., 1998).
49 Ganymede is a unique object in the solar system in that it has its own intrinsic magnetic field which
50 interacts with the Jovian magnetosphere (Kivelson et al., 1997). Within the open field line regions
51 at higher latitudes, sputtering generates an atmosphere of molecular oxygen subject to ionization
52 and dissociated excitation from the Jovian magnetosphere (Eviatar et al., 2001). Within closed
53 field line regions, it is expected the atmosphere is produced by sublimation (Alexander et al.,
54 1999). It is thought the ionosphere is generated from the neutral atmosphere via photoionization
55 and electron impact from the Jovian magnetosphere (Carnielli et al., 2019). Prior to Juno's
56 encounter with Ganymede, the only direct measurements of Ganymede's ionosphere were those
57 acquired in-situ measurements from the Galileo particle detectors and by the Galileo radio
58 occultation experiment. Due to the flyby distance of the in-situ spacecraft measurements, radio
59 occultation data provide valuable information about the electron densities near the surface of
60 Ganymede.

61 The Galileo spacecraft executed a total of eight S-band radio occultations of Ganymede
62 throughout its mission, resulting in five non-detections, two weak detections, and one strong
63 detection of an ionosphere (McGrath et al., 2004). To the best of our knowledge, the Galileo radio
64 science data at Ganymede were never archived. In particular with respect to Ganymede, only
65 occultation profiles from the G8 encounter were ever published in scientific literature. The strong
66 ionosphere detection occurred during the Ganymede G8 egress occultation resulting in a peak

67 electron density of $\sim 5000 \text{ cm}^{-3}$ near the surface (Kliore, 1998). Initially, the lack of detection was
68 surprising, but it was hypothesized that positive detections occurred where the trailing hemisphere
69 (where the magnetospheric plasma impacts the moon) of the satellite was in sunlight; therefore,
70 the atmosphere created by sputtering effects from the Jovian magnetosphere can be can be ionized
71 by solar radiation to produce an observable ionosphere (Kliore et al., 2001).

72 On June 7, 2021, the Juno spacecraft performed a close flyby of Ganymede (Hansen et al.,
73 2022). During this flyby, the spacecraft was occulted by Ganymede as viewed from Earth.
74 Coherent radio links were established during the flyby to enable a radio occultation experiment
75 and gravity experiment to investigate the interior structure (Gomez-Casajus et al., 2022). This
76 article presents the analysis and results of Juno's radio occultation experiment at Ganymede. It is
77 concluded with an interpretation of the resultant ionospheric electron density profiles in the context
78 of current knowledge of Ganymede's tenuous atmosphere and variable ionosphere.

79 **2 Occultation Experiment with Juno**

80 The Juno Gravity Science Instrument (Asmar et al., 2017) is a radio science instrument
81 which utilizes dual-frequency X-band (8.4 GHz) and Ka-band (32 GHz) radio links between the
82 Juno spacecraft and the Earth-based observing stations of NASA's Deep Space Network (DSN).
83 On June 7, 2021 Juno's extended mission trajectory took the spacecraft on a close encounter with
84 Ganymede at an altitude of 1045 km. An Earth occultation occurred during this flyby as shown in
85 Figure 1. Geometric information is summarized in Table 1. Measurement of Ganymede's
86 ionosphere is made via a radio occultation geometry, where the Juno spacecraft set behind
87 Ganymede as observed from Earth. In this way, the radio ray path propagates directly through the
88 ionosphere of Ganymede twice, once on ingress and once on egress. During the radio occultation,
89 Juno transmitted dual-frequency X-band and Ka-band to the 70-meter DSS-43 and 34-meter DSS-
90 35 antennas at the Canberra DSN complex. The occultation experiment was executed in a coherent
91 mode with the downlink signal coherent with the uplink. Both downlink signals were referenced
92 to a single X-band uplink signal sent from the DSS-35 antenna.

93 Several hours prior to occultation, the DSS-35 antenna transmitted an X-band uplink signal
94 to the spacecraft with a typical uplink acquisition sweep. The acquisition sweep transmits a range
95 of frequencies ($\pm 10 \text{ kHz}$ at 200 Hz/sec) around the spacecraft transponder's best lock frequency
96 which takes 170 seconds to execute. The transponder locked to this signal and phase-coherently
97 transmitted X-band and Ka-band back to Earth at ratios of 880/749 and 3360/749, respectively.
98 Upon occultation ingress, the transponder unlocked from the uplink signal due to the loss of signal.
99 In order to re-acquire the signal as quickly as possible on egress, a "snap-lock" technique was
100 utilized. In a snap-lock, an uplink acquisition sweep is not executed and instead relies on precisely
101 targeting the spacecraft transponder's best lock frequency to within the pull-in range of 1.3 kHz.
102 For this technique, two effects are carefully considered: a prediction of the oscillator frequency
103 based upon the temperature of the oscillator; and a prediction of the estimated Doppler shift in the
104 uplink signal. The snap-lock on egress was successful and the transponder re-locked to the uplink
105 signal less than 1 second after geometric occultation egress (corresponding with $\sim 5.9 \text{ km}$ in
106 altitude). Due to the fast flyby velocity ($\sim 18.6 \text{ km/sec}$), without a snap-lock, egress occultation
107 data would have been lost.

108 **3 Methodology**

109 Radio occultation experiments are well-known planetary science methods widely used to
110 perform remote sensing of planetary atmospheres of Solar System bodies, in particular to retrieve
111 vertical profiles of ionosphere electron density and neutral atmosphere physical quantities. The
112 basics of radio occultation experiments for planetary science applications have been presented by
113 (Fjeldbo and Eshleman, 1965; Kliore et al., 1965; Fjeldbo and Eshleman, 1968; Phinney and
114 Anderson, 1968; Fjeldbo et al., 1971). In this technique, the spacecraft transmits a radio signal
115 from the onboard radio to Earth, where it is received by a large ground antenna. As the spacecraft
116 sets behind an object, as viewed from Earth, the radio link will propagate through the object's
117 atmosphere and ionosphere, and it experiences refraction. While investigating ionospheres,
118 refraction due to electrons encountered along the radio ray path causes the signal to bend towards
119 regions of higher index of refraction. This bending produces a phase change in the radio signal
120 proportional to the electron content encountered along the ray path, and it is measured by the
121 ground receiver as a frequency shift. In this context, a dual-frequency analysis is particularly
122 powerful, since it isolates the effect of free-electrons and allows to derive the total electron content
123 and, under certain hypotheses, the local electron density. This analysis adapts methodology as
124 described by Phipps and Withers (2017) and Dalba and Withers (2019) which is briefly described
125 in the following sections.

126 **3.1 Signal Processing**

127 Radio Science utilizes radiometric tracking data collected by the DSN. The preferred
128 method for radio occultation experiments utilizes the Open-Loop Receivers (OLR). The OLR
129 digitally down-converts and records the full spectrum at a user-defined sample rate. The OLR
130 relies on predicted downlink frequencies based on the Doppler shift caused by the motion of the
131 spacecraft trajectory to remain tuned to the incoming signal, without having a feedback loop to be
132 used to track and lock the received signal. This is particularly advantageous in radio occultation
133 experiments, where it is challenging to establish and/or maintain the signal lock near the surface
134 where the signal will be lost and re-acquired. Occultation data were processed from open-loop
135 recordings at 1 kilosamples per second (in-phase and quadrature). The frequency time series are
136 retrieved by processing the OLR data through a spectral fast-Fourier transform algorithm (Paik
137 and Asmar, 2011), in order to obtain a sufficiently high number of frequency measurements. Due
138 to the fast flyby of Ganymede by Juno, the integration time-step of 1 second was selected. This
139 resulted in a satisfactory trade-off between the number of measurements in order to have enough
140 vertical resolution to probe Ganymede's tenuous ionosphere, and the thermal noise.

141 **3.2 Differential Frequency Technique**

142 The differential frequency, or dual-frequency, technique uses two frequencies
143 simultaneously to determine the structure of a planetary body's ionosphere. This method allows
144 for the removal of the classical Doppler shift, as well as the non-dispersive effects, such as neutral
145 atmosphere contributions, and the time variation of the uplink frequency as seen by the spacecraft
146 (clock source). In this way it is possible to isolate the effect of free electrons, which is frequency
147 dependent, on rays traversing the ionosphere.

148 As shown in Equation 1 (Dalba and Withers, 2020), the received frequency, f_R , differs from
149 the transmitted frequency, f_T . This is due to the classical Doppler shift (which can be computed
150 using Equation 1 of Schinder et al. 2015), a shift due to plasma along the ray path, and a shift due
151 to neutral gas along the ray path, respectively. The frequency shift due to the charged particles is

152 inversely proportional to the transmit frequency f_T . In this way, it is possible to take advantage of
 153 multiple frequencies to directly measure the electron content along the radio ray path.

$$f_R = f_T - \frac{f_T}{c} \frac{d}{dt} \int dl + \frac{e^2}{8\pi^2 m_e \epsilon_0 c f_T} \frac{d}{dt} \int N_e dl - \frac{f_T \kappa}{c} \frac{d}{dt} \int n dl \quad (1)$$

154 where l is the path length, c is the speed of light, t is time, e is the elementary charge, m_e is
 155 the electron mass, ϵ_0 is the permittivity of free space, N_e and n are the electron density and neutral
 156 density at a given point, respectively, and κ is the refractive volume of neutral gas at a given point.

157 During the occultation, the spacecraft transmitted frequencies at X-band ($f_{T,X}$) and at Ka-
 158 band ($f_{T,Ka}$). The frequencies precisely related by the ratio of the turnaround ratios, i.e. $f_{T,Ka}/f_{T,X} =$
 159 3360/880. Differential frequency residuals are then obtained as a function of time in Equation 2.

$$\Delta f(t) = f_{R,X}(t) - \frac{880}{3360} f_{R,Ka}(t) = \frac{e^2}{8\pi^2 m_e \epsilon_0 c f_{T,X}} \left(1 - \left(\frac{880}{3360} \right)^2 \right) \frac{d}{dt} \int N_e dl \quad (2)$$

160 As a result, the plasma column density along the ray path $\int N_e dl$, or Total Electron Content
 161 (TEC), as a function of time, can be directly obtained from time series of received frequencies at
 162 X- and Ka-band. Because the dual-frequency link is only present on the downlink, the retrieved
 163 TEC is referred to the downlink radio ray path only.

164 Before obtaining the TEC and local electron density, it is crucial to calibrate the differential
 165 frequency residuals of Equation 2 for the solar plasma and Earth's ionosphere, in order to obtain
 166 reliable results. If not calibrated, these effects could jeopardize the accuracy of the retrieved
 167 electron densities. The noises can be evaluated in the baseline of the residual frequencies, the
 168 region where the signal is traveling outside the ionosphere of Ganymede. The baseline should be
 169 flat with low-noise and zero-mean residual frequencies. In the case of Juno, the largest effect on
 170 the dual-frequency residuals is that of the spin-phase wrapping (Marini, 1971). A bias offset is
 171 evaluated in the baseline and subtracted to the entire observation time-span of the differential
 172 frequency residuals.

173 After calibration, Equation 2 is integrated with respect to time and obtain the TEC using
 174 Equation 3. This is then translated into a function of the closest approach distance of the radio ray
 175 path to the center of mass of Ganymede using the spacecraft and planetary ephemerides, where X
 176 is the closest approach distance.

$$TEC(X) = \int N_e dl = \int \frac{8\pi^2 m_e \epsilon_0 c f_{T,X}}{e^2 \left(1 - \left(\frac{880}{3360} \right)^2 \right)} \Delta f(t) dt \quad (3)$$

177 Following (Dalba and Withers, 2020), and assuming that Ganymede's ionosphere is locally
 178 spherically symmetric, the vertical profiles of Ganymede's electron density are obtained using an
 179 Abel transform inversion formula, starting from the TEC (Fjeldbo et al., 1971; Hinson et al., 1999;
 180 Withers, 2020) using Equation 4.

$$N_e(r) = \frac{1}{\pi} \int_{X=r}^{X=\infty} \ln \left(\frac{X}{r} + \sqrt{\left(\frac{X}{r}\right)^2 - 1} \right) d \left(\frac{dTEC(X)}{dX} \right) \quad (4)$$

181 where r is the radial distance. Consequently, the vertical profile of the ionospheric electron
 182 density $N_e(r)$, is derived from the integrated plasma column density (TEC). In the Abel transform,
 183 it is assumed that the ionosphere is spherically symmetric at the occultation point. The non-
 184 spherical nature of Ganymede's ionosphere could possibly lead to biases in electron density results
 185 at the icy moons of Jupiter in certain geometries (Kliore 1998). However, since the index of
 186 refraction of the ionosphere is very small (it deviates from 1 by about 10^{-9} in the part of the
 187 ionosphere where the electron density is maximum), the rays do not bend significantly and they
 188 can safely be assumed to follow straight lines. Thus, the Abel transform should still result in
 189 accurate electron density profiles, for example, as assumed for Saturn and Titan (Schinder 2020).

190 4 Results

191 The analysis of the ingress leg of the experiment uses data beginning at 16:48:00.0 after
 192 spacecraft telemetry was turned off, until 17:18:55.1. Although actual loss of signal at Ka-band
 193 occurs 1 second later at 17:18:56.1, effects of diffraction are observed and the data cutoff was
 194 chosen to occur prior to this (see Text S1 of Supporting Information). The egress leg consists of
 195 data between the time of signal re-acquisition at 17:32:38.0 until the 17:52:00.0 when a second re-
 196 acquisition sweep was executed. All times are stated in UTC as received on Earth (Earth Receive
 197 Time). Because it took the spacecraft transponder \sim 1-2 seconds to re-acquire the uplink signal on
 198 egress, and the non-coherent portion was not used, diffraction does not affect egress.

199 The ingress occultation occurred in the southern hemisphere of the moon at latitude 59° S,
 200 while the egress occultation occurred 15 minutes later in the northern hemisphere at latitude 20° N.
 201 In terms of magnetospheric geometry, both ingress and egress occurred near the terminator. The
 202 egress occultation point was partially sun-lit as well as contained in Ganymede's magnetospheric
 203 wake. As a result, ingress was characterized by a small Ram angle, and egress by a small Solar
 204 Zenith angle, and either one (if not both) of these conditions are considered favorable for the
 205 detection of an ionosphere.

206 Figure 2 shows the dual-frequency residuals (in Hz), which were obtained using Equation
 207 2 for ingress (panel a) and egress (panel b). The data were calibrated as described in the previous
 208 section, using a baseline defined by ray-path altitudes over Ganymede's surface between 5,000-
 209 11,000 km for ingress, and 5,000-7,000 km for egress. These altitude intervals were selected so
 210 that the baselines are completely outside of Ganymede's ionosphere. Nevertheless, the results are
 211 stable regardless of the baseline chosen to perform the calibrations, down to an altitude of about
 212 1,500 km.

213 After calibration, the profiles of dual-frequency residuals are directly converted using
 214 Equation 3 into profiles of Total Electron Content (TEC), a measure of column density of electrons
 215 (10^{16} m^{-2}). The TEC shows there is a clear accumulated ionosphere signal at low altitudes below
 216 800 km during the ingress occultation but such signal is not detected on the egress occultation,
 217 which remains relatively constant (see Figure S4 in Supporting Information).

218 The TEC represents the column density obtained integrating the electron density N_e along
 219 the ray path, and is, therefore, an average measurement. To retrieve the local electron density (in

220 cm^{-3}) as a function of altitude, an Abel transform is performed on the TEC profile using Equation
 221 4. The key assumption for using this algorithm is that of local spherical symmetry of the satellite
 222 around the occultation point. The electron density is plotted once again against the altitude above
 223 the surface of the satellite (Figure 3). For both ingress and egress the vertical resolution is ~ 5.9 km
 224 (at 1 second integration time) which is largely dependent on the flyby velocity. In order to mitigate
 225 the effect of thermal noise, 1000 electron density profiles were generated by beginning the
 226 frequency estimation with subsequent open-loop samples (1000 profiles are generated with a
 227 sampling rate of 1 kHz). The profiles were then averaged (see Text S2 in Supporting Information).
 228 These results show that there is an elevated electron density near the surface above the $3\text{-}\sigma$
 229 uncertainty level on ingress (Figure 3a). The peak density is approximately $(2000 \pm 500) \text{ cm}^{-3}$ ($1\text{-}\sigma$)
 230 at a 15 km data cutoff altitude. On ingress between 15 km and 1,500 km, the corresponding
 231 scale height H assuming an exponential ionosphere ($e^{-z/H}$) is 1050 ± 110 km. Egress yielded an
 232 observation of $(400 \pm 500) \text{ cm}^{-3}$ ($1\text{-}\sigma$). Although the electron density profile on egress was more
 233 sensitive to the calibration techniques, the averaged profile is statistically compatible with zero at
 234 the $3\text{-}\sigma$ level with one exception around 1,800 km. Due to the high altitude and sensitivity to the
 235 baseline calibration, is likely not associated with the ionosphere and therefore we conclude egress
 236 does not show a detection of an ionosphere (Figure 3b).

237 Thermal, instrumental, and propagation noise sources are present in the data. The
 238 dominating noise in the observation is thermal. Instrumental noise is negligible, since the oscillator
 239 stability and atmospheric effects cancel in the dual-frequency combination, leaving only hardware-
 240 related sources with estimated Allan deviation stability on the order of $\sim 10^{-16}$ to $\sim 10^{-15}$ at 1000-sec
 241 (Asmar et al 2005). Propagation sources of error from plasma are also present and include
 242 fluctuations in the Earth's ionosphere and solar plasma. The local time of the ray path through
 243 Earth's ionosphere occurred during night, when ionosphere activity is lower than daytime. These
 244 variations in Earth's ionosphere during the occultation timeframe were small as measured by
 245 GNSS receivers located at the DSN antennas. When calibrated, it did not change the results. Solar
 246 plasma noise is the other propagation noise source. The larger drift trend of solar plasma is
 247 removed in the background polynomial fit. Solar plasma scintillation at the solar elongation angle
 248 of 105° during Ganymede's occultation corresponds with an X-band scintillation noise of 0.75
 249 mHz (after conversion from Asmar et al (2005) from Allan deviation of $\sim 2 \times 10^{-14}$ at 1000-sec),
 250 therefore we do not expect this effect to dominate the data noise when compared with the thermal
 251 noise levels of nearly twice that. However, undesired solar plasma noise may still be present in the
 252 observation. The error bars (represented by shaded regions) were estimated through means of a
 253 Monte Carlo analysis by adding gaussian random noise time-series (whose σ is consistent with the
 254 observed noise outside Ganymede's ionosphere) to the original differential frequency residuals, in
 255 order to obtain the standard deviations of the profiles in terms of electron density. The $1\text{-}\sigma$ (~ 500
 256 cm^{-3}) and $3\text{-}\sigma$ uncertainties ($\sim 1500 \text{ cm}^{-3}$) derived from the Monte Carlo analysis is consistent with
 257 an uncertainty estimated using the method described by Withers, 2020.

258 5 Discussion

259 Ganymede's atmosphere is generated by charged particle sputtering and sublimation from
 260 the icy surface with detections by Hubble Space Telescope (Hall et al, 1998 & Roth et al, 2021).
 261 In the context of the Juno occultation measurements, ingress and egress occultation points appear
 262 to be in ice-rich regions (Ligier et al., 2019) where this can occur. Ganymede's ionosphere is
 263 generated from the neutral atmosphere through photo-ionization and electron-impact ionization

264 from Jupiter's magnetosphere (Carnielli et al., 2019). Juno's radio occultation are observed at the
265 closest point to the surface of Ganymede along the ray path between the spacecraft and Earth. In
266 this geometry, ingress was in the shadow whereas egress was in a sun-lit region (Figure 1). When
267 comparing occultation points with open-closed field line boundaries of Ganymede's
268 magnetosphere (either from Duling et al (2022) or Jia and Kivelson, 2021), it is evident that ingress
269 occurred in the open-field line region and egress likely occurred in the closed-field line regions.
270 Since electron-impact ionization rates would be higher in open field-line regions, the Juno
271 occultation sheds light on the generation mechanisms for Ganymede's ionosphere.

272 The stark contrast in the geometry of the Juno occultation – ingress in the shadow, but open
273 field-line and egress sun-lit, but in closed field-line region – indicates that electron-impact
274 ionization plays an important role in generating Ganymede's ionosphere in the open-field line
275 region. This is corroborated by the strong detection of the ionosphere by Galileo radio occultation.
276 The G8 egress occultation, occurring at a latitude of 47° N and west longitude of 22° (Kliore 1998),
277 was also in the open field-line region defined by Jia and Kivelson, 2021.

278 Previous modeling efforts of Ganymede's ionosphere have been conducted by Eviatar et
279 al 2001, Carnielli et al 2019, and Carnielli et al 2020. Eviatar et al 2001 modeled the surface density
280 of electrons is about 400 cm^{-3} with a scale height of 600 km. Near the surface, the scale height may
281 be considerably smaller yielding a higher surface density. Although the modeled surface density
282 is well below an upper limit obtained by the Galileo radio occultation measurement, Eviatar et al
283 2001 also show that the peak electron densities measured by Kliore (1998) do not contradict a
284 model of the ionosphere in the polar cap region due to large uncertainties in atomic and
285 environmental parameters. Juno's ingress occultation observation of 2000 cm^{-3} is lower than the
286 upper limit set by Galileo G8 egress occultation and thus the Juno occultation results not exclude
287 this upper limit from possibilities either. Extending on Carnielli et al 2019, Carnielli et al 2020
288 proposed that increasing neutral atmosphere densities or increased electron-impact ionization rates
289 can explain discrepancies between observations and models.

290 Juno successfully executed a radio occultation of Ganymede during a close encounter on
291 June 7, 2021. Both ingress and egress electron profiles were obtained using a dual-frequency
292 technique. On ingress, an ionosphere signature was detected with a peak electron density of 2000
293 ± 500 ($1-\sigma$) cm^{-3} at 15 km with a scale height of 1050 ± 110 km. On egress, no statistically
294 significant ionosphere was detected. Thus, at first glance the Juno occultation results appears
295 consistent with results of the Galileo occultation campaign where only one strong detection of an
296 ionosphere was observed with a peak of approximately 5000 cm^{-3} at 16 km (Kliore 1998) out of
297 eight occultation profiles. With current knowledge of the interaction between Ganymede's
298 atmosphere, ionosphere, and Jupiter's magnetosphere, we conclude that the reason for the ability
299 to detect an ionosphere with the radio occultation technique is due to higher electron impact
300 ionization rates in open-field line regions, where positive detections of the ionosphere occur.

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316 **Data Availability Statement**

317 The Juno radio science data used in this research are publicly available through NASA's Planetary
 318 Data System at https://atmos.nmsu.edu/PDS/data/jnogrv_1001/ (Buccino, 2016). The occultation
 319 results presented here are provided in a corresponding dataset with this publication on Zenodo
 320 (Buccino, 2022).

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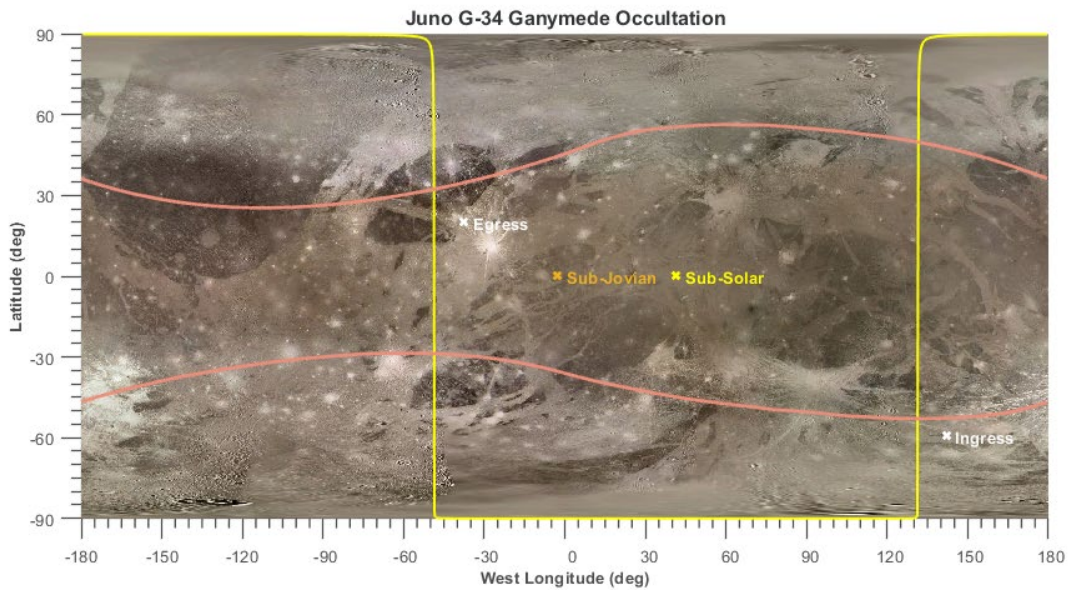
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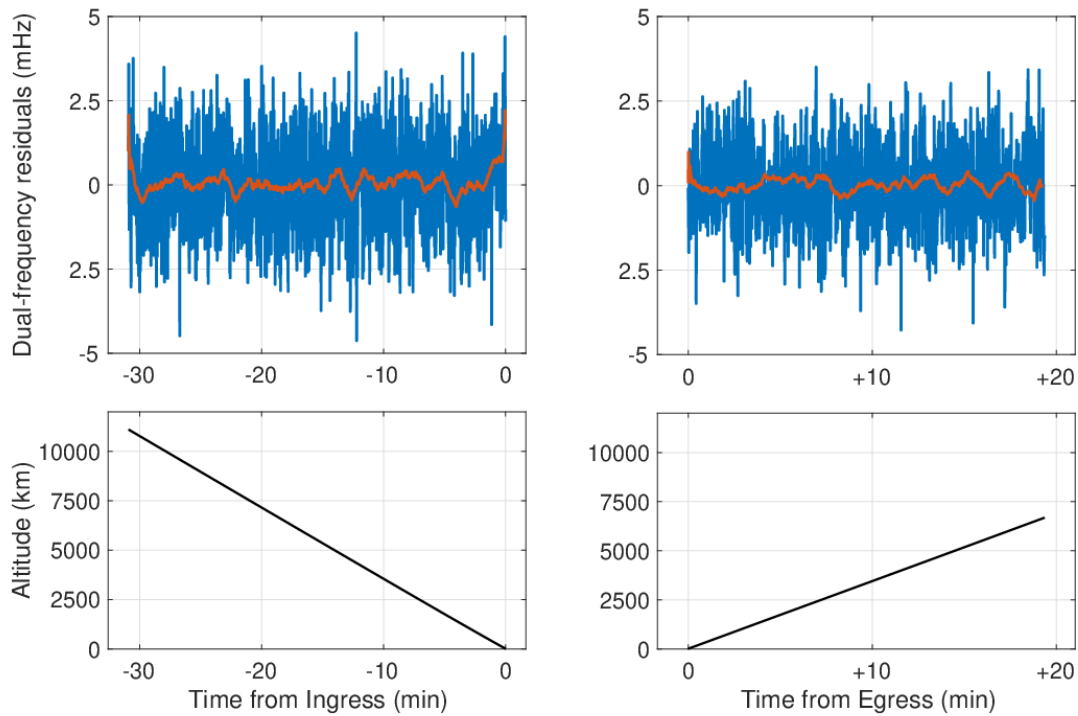
392

393 **Figure 1.** Geometry of the Juno G-34 flyby and radio occultation points. The occultation ingress
 394 point was just outside the terminator at $-142^{\circ}\text{W} / 59^{\circ}\text{S}$ and egress occurred just inside the
 395 terminator near the spacecraft ground track at $38^{\circ}\text{W} / 20^{\circ}\text{N}$. The spacecraft ground track is shown

396 in white, sun terminator in yellow, and sub-Jovian point in orange. Overlaid in light red are the
 397 open/closed field line boundaries from Duling et al (2022).

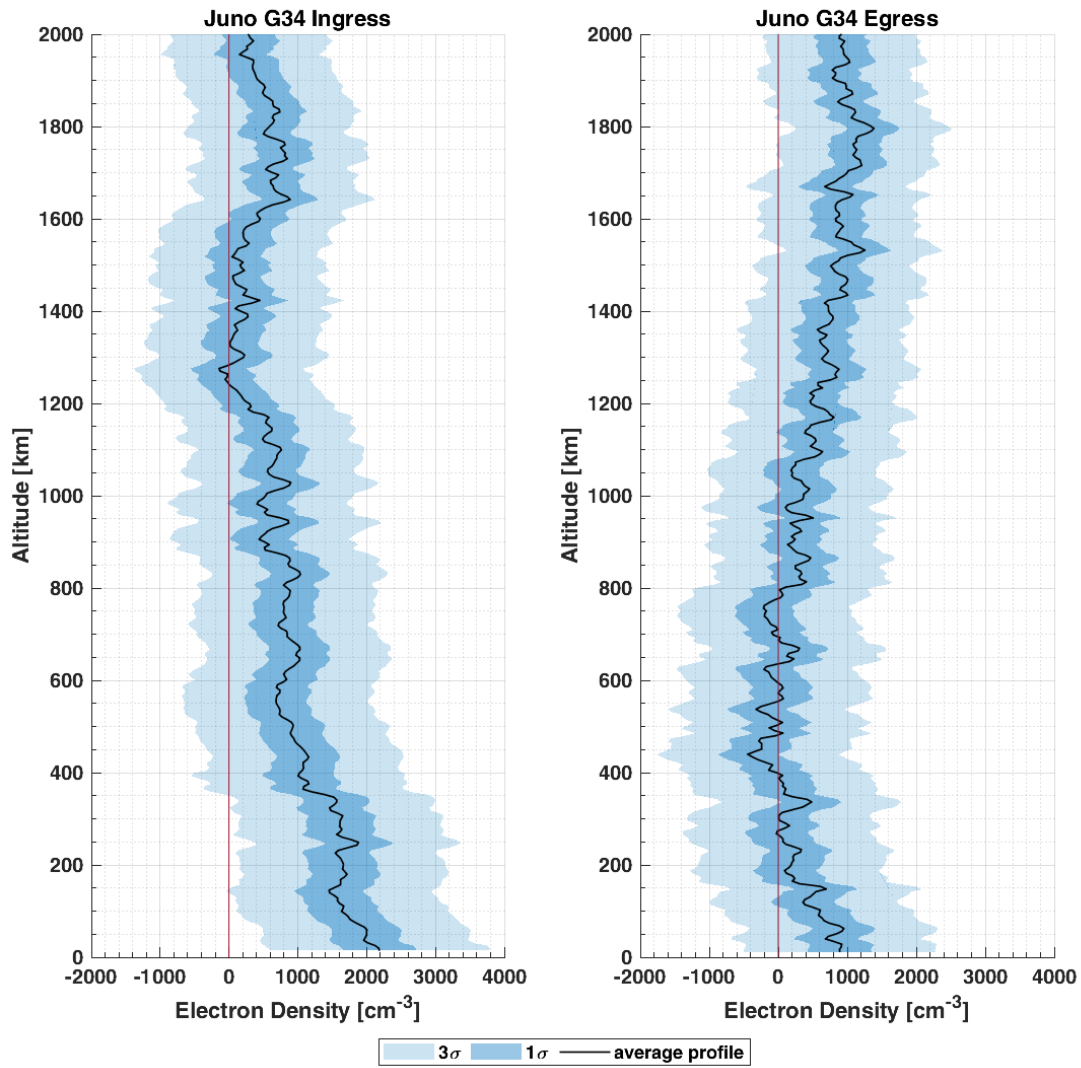
398 **Table 1.** Geometry of the Juno radio occultation of Ganymede. Parameters are given at the
 399 occultation point (closest point along the radio propagation path to Ganymede).

Observation	Occultation (UTC Earth Receive)	Time	Distance (km)	Lat. (deg)	W. Long. (deg)	Solar Zenith Angle (deg)	Ram Angle (deg)
Juno G34 Ingress	2021-Jun-07 17:18:57		18,094	59° S	-142° W	95°	72°
Juno G34 Egress	2021-Jun-07 17:32:38		3,772	20° N	38° W	80°	125°



400

401 **Figure 2.** Plots of the 1-second integration time (blue) and 60-second average (red) dual-frequency
 402 residuals (Hz) for the ingress (a) and egress (b) occultations as a function of time, along with plots
 403 of the ray path altitude over the surface of Ganymede (c, d), during the occultations.



404

405 **Figure 3.** Electron density within Ganymede's ionosphere during ingress occultation (a) and
 406 egress occultation (b). The dark and light blue shaded area represent the 1- σ and 3- σ uncertainties,
 407 respectively.