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Audrey Chatain, J.-E. Wahlund, O. Shebanits, L. Z. Hadid, M. Morooka, et al.. Re-analysis of the Cassini RPWS/LP data in Titan's ionosphere. Part I: detection of several electron populations. *Journal of Geophysical Research Space Physics*, 2021, 126 (8), pp.e2020JA028412. 10.1029/2020JA028412 . insu-03298835

HAL Id: insu-03298835

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Submitted on 26 Jul 2021

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1 **Re-analysis of the Cassini RPWS/LP data in Titan's ionosphere. Part I: detection of**
2 **several electron populations**

3
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11

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13

14 **Key Points:**

- 15 • The Cassini Langmuir probe dataset in Titan's ionosphere is re-analyzed with a specific
16 interest on the electron density and temperature.
- 17 • 2 to 4 cold electron populations with distinct potentials are observed.
- 18 • Electron populations vary with altitude and solar illumination suggesting origins linked to
19 solar photons, magnetospheric particles and dust

20

21

22 **Abstract**

23 Current models of Titan’s ionosphere have difficulties in explaining the observed electron density
 24 and/or temperature. In order to get new insights, we re-analyzed the data taken in the ionosphere
 25 of Titan by the Cassini Langmuir probe (LP), part of the Radio and Plasma Wave Science (RPWS)
 26 instrument. This is the first of two papers that present the new analysis method (current paper) and
 27 statistics on the whole dataset. We suggest that between 2 and 4 electron populations are necessary
 28 to fit the data. Each population is defined by a potential, an electron density and an electron
 29 temperature and is easily visualized by a distinct peak in the second derivative of the electron
 30 current, which is physically related to the electron energy distribution function (Druyvesteyn
 31 method). The detected populations vary with solar illumination and altitude. We suggest that the
 32 4 electron populations are due to photo-ionization, magnetospheric particles, dusty plasma and
 33 electron emission from the probe boom, respectively.

34

35 **1 Introduction**

36 The Cassini mission explored the Saturnian system from 2004 to 2017 and gave us unprecedented
 37 insights on the ionosphere of Titan, the biggest moon of Saturn (Coates et al., 2007; Wahlund et
 38 al., 2005; Waite et al., 2005). This ionized environment hosts a complex ion chemistry that leads
 39 to the formation of organic aerosols (Vuitton et al., 2019; Waite et al., 2007). The Cassini mission
 40 investigated Titan at the occasion of 126 close flybys, and probed the ionosphere below the altitude
 41 of 1200 km for 57 of these flybys. There is a substantial coverage of measurements taken at
 42 different solar zenith angles, latitudes and seasons, enabling statistical analyses.

43 The study here is focused on electrons in Titan’s ionosphere. The electron density was previously
 44 observed to be mainly governed by solar photons during the day (Ågren et al., 2009).
 45 Photoionization of the neutral molecules lead to a maximum electron density ($\sim 2000 \text{ cm}^{-3}$) around
 46 1100 km altitude. The electron density have also been observed to vary (up to factor 2 at the peak)
 47 with the solar cycle (Edberg et al., 2013). On the nightside, electron transport from the dayside
 48 and the thermalization of magnetospheric electrons give a constant electron density of $\sim 400\text{-}700$
 49 cm^{-3} from 1200 km to < 950 km (Ågren et al., 2009; Cravens et al., 2009; Cui et al., 2009; Shebanits
 50 et al., 2017b).

51 Below 1100 km of altitude, positive, negative ions and dust have increasing densities, and start to
 52 affect the electrons (Shebanits et al., 2013, 2016; Waite et al., 2007). In particular, dust particles
 53 in a dense ionized environment tend to attract electrons and charge negatively (e.g. Farrell et al.,
 54 2009; Shukla & Mamun, 2015). It explains why the electron density decreases below 1100 km,
 55 while the density of ions and negatively charged dust increase and become the dominant negative
 56 charge carriers (e.g. Shebanits et al., 2013, 2016).

57 The temperature of the bulk electrons can be deduced from measurements by the Langmuir probe
 58 on-board Cassini. Ågren et al. (2009) and Edberg et al. (2010) derived the electron temperature
 59 profiles (assuming a single Maxwellian electron distribution) from 52 flybys down to ~ 900 km of
 60 altitude and stated a rather stabilized temperature below 1100 km. The observed values ranged
 61 from 0.03 to 0.06 eV ($\approx 350\text{-}700$ K).

62 Several models have been developed to understand the processes at work in Titan’s ionosphere
 63 (e.g. Galand et al., 2014 and references therein). Nevertheless, model results either predict too cold

64 electrons (< 0.02 eV; < 200 K) at 900 km (Mukundan & Bhardwaj, 2018; Richard et al., 2011) or
65 an overestimated electron density by a factor of 2 (Vigren et al., 2013, 2016). The addition of the
66 negative ions to a photoionisation model has been shown to decrease the discrepancy with the
67 measurements (Shebanits et al., 2017a).

68 The present work aims to closely investigate the measurements of the electron density and
69 temperature in the ionosphere of Titan, focusing on the interaction between electrons and negative
70 ions and dust. For this purpose, we re-analyzed the measurements acquired by the Langmuir probe
71 (LP) part of the Radio and Plasma Wave Science (RPWS) investigation on-board Cassini, during
72 the 13 years of the mission. This work is presented in two parts. In a first paper (this one), we detail
73 the method used for the re-analysis of the data and the detection of several electron populations.
74 A second paper (Chatain et al., n.d.), referred as ‘paper II’, presents the results obtained for 57
75 flybys and discusses the origins of the detected electron populations.

76

77 **2 Methods**

78 **2.1 Langmuir Probe measurements**

79 The Langmuir probe on-board Cassini was built by the Swedish Institute of Space Physics (IRF).
80 It was positioned below the radio antenna, on a 1.5 m boom to minimize electric perturbation from
81 the spacecraft (Gurnett et al., 2004). The probe was a sphere of titanium of 5 cm in diameter, coated
82 with titanium nitride, chosen foremost for its electrical work function stability, chemical inertness,
83 high reflectivity and limited photoelectric effects. It is also very hard, enhancing solid particle
84 impact resistance and eliminating hysteresis effects that are observed with other surface coatings
85 (Wahlström et al., 1992). A small part of the stick (the stub) closest to the sphere was kept at the
86 probe potential to ensure a symmetric potential pattern and sampling around a swept probe. A
87 cleaning mode enabled to remove a possible contamination on the surface. In this mode, the
88 potential of the sphere was set at +32 V to induce sputtering of the probe with high energy
89 electrons.

90 In this study, we used the measurements from the sweep mode of the probe. The current collected
91 by the probe during the voltage sweep enables to deduce the electron density and temperature
92 (among other useful derived parameters of interest). On Titan, the probe usually acquired double-
93 sweeps, in 512 x2 voltage steps, from +4 V to -4 V, and back to +4 V, to give an idea of possible
94 surface contamination effects. In addition, to detect any charging effects, for both of the sweeps
95 the current was measured twice at each voltage step.

96 In this work, we first investigated the reproducibility of the measurements with the two voltage
97 sweeps (named ‘down’ and ‘up’), and the double measurements at each voltage step (resp.
98 ‘down1’-‘down2’ and ‘up1’-‘up2’). We observed that ‘down1’ and ‘down2’ are always very close
99 to each other: the current stabilizes quickly after each voltage step. However, during the increasing
100 voltage phase (‘up1’ and ‘up2’), the current continues to increase slightly between the two
101 measurements. Further details are given in Appendix A.

102 In the following, we did not take the average of ‘down’ and ‘up’ because in some cases a shift in
103 the measured plasma potential between both would distort the average signal. We generally used
104 the average of the decreasing part of the sweep (‘down’). Nevertheless, we used also the average
105 of ‘up1’ and ‘up2’ in the few cases where the decreasing part of the sweep was not acquired. We

106 analyzed the impact of using the ‘down’ or the ‘up’ signal in our study and concluded that this
 107 effect was negligible compared to the fit error bars (see further). An example is given in Supporting
 108 Information Figure S1.

109

110 2.2 Theory to fit the electron and positive ion current

111 The Orbital Motion Limited (OML) theory is used to fit the voltage sweeps measured by the
 112 Langmuir probe. A correction is added in the attractive bias voltage region using the Sheath
 113 Limited theory (SL).

114 The OML theory, first described by Mott-Smith & Langmuir (1926), deduces information on the
 115 charged particles from the current measured by the probe, based on the conservation of energy and
 116 angular momentum. No particle is assumed to come from the probe itself and the bulk particle
 117 speed distribution is assumed Maxwellian. The OML theory is valid when the probe radius is
 118 smaller than the Debye length in the probed region. In these conditions, the electron and ion
 119 currents (respectively I_e and I_i) are described by two different equations depending on the sign of
 120 $\Delta U = U_{bias} - U_p$ (Wahlund et al., 2009; Whipple, 1965), U_{bias} being the potential of the probe
 121 and U_p the characteristic potential of the electron/ion population in the plasma. The electron
 122 current I_e (resp. the ion current I_i) is expressed as a function of $I_{e,0}$ (or $I_{i,0}$) and χ_e (resp. χ_i):

$$I_x = I_{x,0} (1 - \chi_x) \quad x = e \text{ if } \Delta U > 0, x = i \text{ if } \Delta U < 0 \quad (1)$$

[‘attractive’ part for electrons]

$$I_x = I_{x,0} \exp(-\chi_x) \quad x = e \text{ if } \Delta U < 0, x = i \text{ if } \Delta U > 0 \quad (2)$$

[‘repelling’ part for electrons]

123 The two equations join in $\Delta U = 0$. Then, the collected current $I_{x,0}$ is formulated as follows. It
 124 combines the effect of flow kinetic energy and thermal energy (Fahleson et al., 1974):

$$I_{x,0} = -A_{LP} \cdot n_x \cdot q_x \cdot \sqrt{\frac{v_x^2}{16} + \frac{k_B T_x}{2\pi \cdot m_x}} \quad (3)$$

125 A_{LP} is the surface area of the probe. n_x , q_x , v_x , T_x and m_x are respectively the density, charge,
 126 velocity, temperature and mass of electrons or ions, and k_B is the Boltzmann constant.

127 The parameter χ_x depends on ΔU and is expressed as:

$$\chi_x = \frac{q_x \cdot \Delta U}{\frac{m_x v_x^2}{2} + k_B T_x} \quad (4)$$

128 In the case of electrons, the flow kinetic energy term can be neglected compared to the thermal
 129 term. It is the opposite in the case of ions (positive and negative), which are heavier than electrons
 130 and transported along the ion ram flux. When $\Delta U \ll 0$, the collected current is governed by
 131 positive ions while it is dominated by electrons when $\Delta U > 0$.

132

133 In Titan’s ionosphere, the Debye length ($\lambda_D \approx 2.5 - 10.5 \text{ cm}$) is similar to the radius of the probe
 134 ($r_p = 2.5 \text{ cm}$). It is the limit of validity to use the OML theory. Therefore, a small correction is
 135 added by using the Sheath Limited (SL) theory (Bettinger & Walker, 1965; Whipple, 1965), valid
 136 in a collisionless maxwellian plasma. It adds the dependence of the sheath thickness (s) with the
 137 potential and size of the probe and changes the expression of the attractive part. For electrons, it
 138 gives for $\Delta U > 0$:

$$I_e = I_{e,0} \times \left[1 + \xi \times \left(1 - \exp\left(-\frac{\chi_e}{\xi}\right) \right) \right]$$

$$\text{with } \xi = \left(\frac{s}{\rho} + 1\right)^2 - 1, \quad \rho = \frac{r_p}{\lambda_D} \quad (5)$$

$$\text{and } s = 0.83 \cdot \sqrt{\chi_e} \cdot \rho^{\frac{1}{3}}$$

139 The expression of the sheath thickness (s) is empirically obtained by Bettinger and Walker (1965)
 140 in the case of spherical bodies. These expressions converge to the OML expressions when $s \gg r_p$.

141
 142 The electron temperature and the Electron Energy Distribution Function (EEDF) can be obtained
 143 from the ‘transition region’, the part of the voltage sweep where the electron current starts to
 144 dominate the positive ion current, i.e. for ΔU being slightly negative (of a few tenths of volts in
 145 the conditions of Titan’s ionosphere).

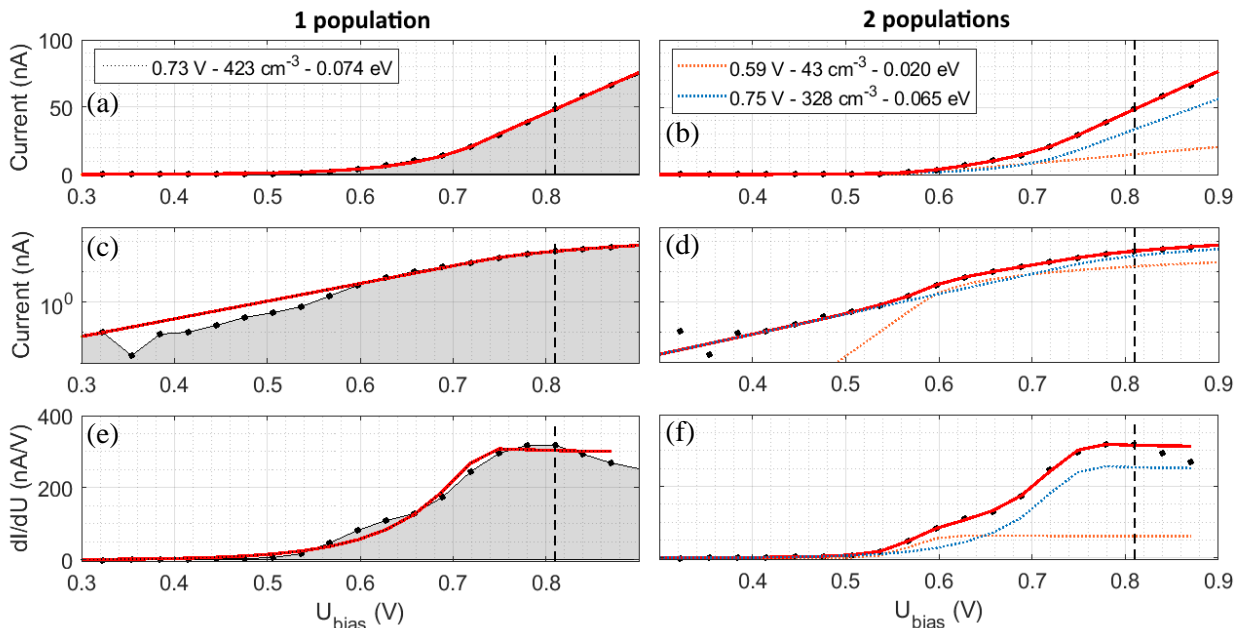
146 In this transition region, the positive ion current is not always negligible compared to the electron
 147 current. To obtain the electron current, the measured (total) current is therefore corrected from the
 148 positive ion part, fitted by a linear curve (see Equation (1)). An example is given in Supporting
 149 Information Figure S2.

150
 151 **2.3 Example of electron current collected in Titan’s ionosphere: observation of several**
 152 **electron populations**

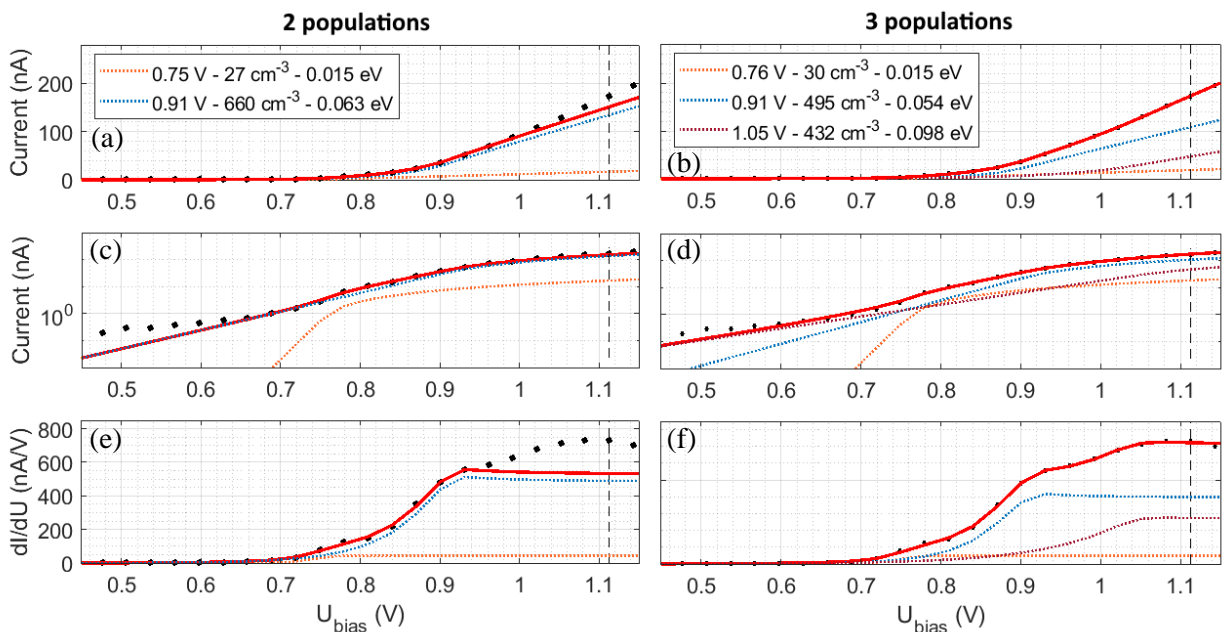
153 The electron part is fitted with Equations (2) and (5). Nevertheless, using only one electron
 154 ‘population’ (i.e. one combination of Equations (2) and (5)) results in a poor fit of the electron
 155 current collected in the ionosphere. Generally, a second population has to be added. It leads to two
 156 different sets of (U_p, n_e, T_e) . An example is shown in Figure 1.

157 Below 1300 km, two maxwellian populations of electrons are often still not sufficient to correctly
 158 fit the electron current. A third, and in rare occasions a fourth, population is required. An example
 159 with three populations is shown in Figure 2 and examples with one and four populations are given
 160 in Supporting Information Figure S3 and S4. In conclusion, the analysis of voltage sweeps in the
 161 ionosphere of Titan often leads to 2-4 sets of (U_p, n_e, T_e) per sweep. The fitting procedure is
 162 detailed in Appendix B.

163



164
 165 **Figure 1.** Fitting of the voltage sweep acquired during T50 at 1241 km altitude. (a,c,e) One electron
 166 population is used for fitting. (b,d,f) Two electron populations are used for fitting. The fit results (U_p, n_e, T_e)
 167 for each population are indicated on the graphs. The part of the curves after the dashed line corresponds to
 168 a part possibly distorted by the effect of a logarithmic pre-amplifier, and should not be used without further
 169 consideration.



170
 171 **Figure 2.** Fitting of the voltage sweep acquired during T50 at 1125 km altitude. (a,c,e) Two electron
 172 populations are used for fitting. (b,d,f) Three electron populations are used for fitting. The fit results
 173 (U_p, n_e, T_e) for each population are indicated on the graphs. The part of the curves after the dashed line
 174 corresponds to a part possibly distorted by the effect of a logarithmic pre-amplifier, and should not be used
 175 without further consideration.

176

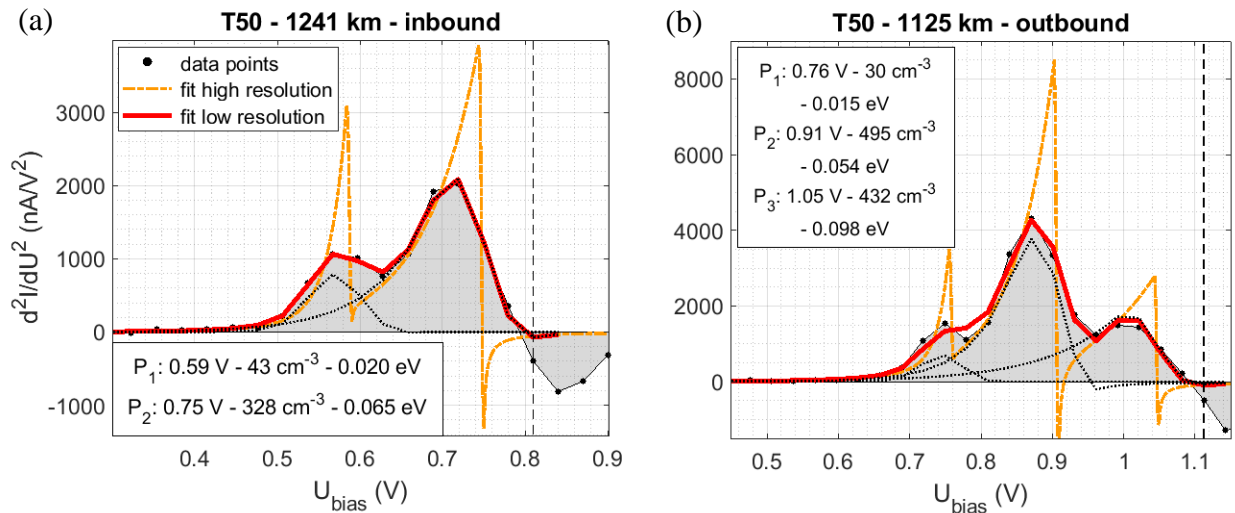
177 2.4 The second derivative of the electron current (d^2I/dU^2): an effective method to detect
 178 the electron populations

179 The second derivative of the current is a good indicator of the presence of several electron
 180 populations. Each peak corresponds to a population, and its area is globally proportional to the
 181 electron density associated (this is explained in Section 2.5). Figure 3 shows d^2I/dU^2 associated
 182 with the fitted sweeps plotted in Figure 1 and 2. Cases with 1 and 4 populations are shown in
 183 Supporting Information Figure S5.

184 The data points are at very low resolution, with only four to ten points per peak. Consequently, the
 185 computation of the second derivative is strongly impacted. This effect is illustrated in Figure 3:
 186 the red curve shows d^2I/dU^2 computed from the fit with the (low) resolution of the data points, and
 187 the orange dotted-dashed line gives d^2I/dU^2 with a high resolution (with >200 points per peak).

188 The confidence intervals on the fit results (U_p, n_e, T_e) for all the populations are also computed
 189 (see details in Appendix C) and are plotted in the Figures of section 3.2. The uncertainty is larger
 190 in the cases with more electron populations, in particular when their parameters U_p are close.

191



192

193 **Figure 3.** Second derivative of current for the sweeps shown in (a) Figures 1 and (b) Figure 2. The fitted
 194 curves shown in Figures 1 and 2 are derived to obtain d^2I/dU^2 , at the resolution of the data points (red line)
 195 and at higher resolution (orange dotted-dashed line). The fit results (U_p, n_e, T_e) for each population are
 196 indicated on the graphs. The part of the curves after the dashed line corresponds to a part possibly distorted
 197 by the effect of a logarithmic pre-amplifier, and should not be used without further consideration.

198

199

200 2.5 Link between the second derivative of the electron current and the Electron Energy
 201 Distribution Function (EEDF)

202 This section explains the link between the second derivative of the current (d^2I/dU^2) and the
 203 Electron Energy Distribution Function (EEDF). It aims to justify the attribution of electrons
 204 populations to peaks in the second derivative. The presented method finally gives the Maxwellian
 205 EEDF of each of the electron populations detected on a same measurement.

206

207 2.5.1 *The Druyvesteyn method*

208 The Druyvesteyn method (Druyvesteyn, 1930; Lieberman & Lichtenberg, 2005) was used to
 209 compute the EEDF from the electron current measured by the Langmuir probe. The method is
 210 valid for any convex probe geometry and does not depend on the probe dimension compared to
 211 Debye length, or on the ratio T_i/T_e . The EEDF is computed from the second derivative of the
 212 current, and the electron density is equal to the integral of the EEDF (see details in Appendix D):

$$EEDF_{Dr}(\Delta U) = \frac{2\sqrt{2}}{A_{LP} e^2} \sqrt{\frac{m_e \cdot (-\Delta U)}{e}} \frac{d^2i}{d\Delta U^2} \quad [J^{-1} \cdot m^{-3}] \quad (6)$$

with $n_e = \int_0^{+\infty} EEDF_{Dr}(E(\Delta U)) \cdot dE$ and $E(\Delta U) = -e \cdot \Delta U$

213 If the Druyvesteyn method is applied to the expression of the current given in Equation (2), it gives
 214 back the expression of an EEDF for a Maxwellian speed distribution:

$$EEDF_{Maxw}(E) = \frac{2}{\sqrt{\pi}} \cdot (k_B \cdot T_e)^{-\frac{3}{2}} \cdot n_e \cdot \sqrt{E} \cdot \exp\left(-\frac{E}{k_B \cdot T_e}\right) \quad (7)$$

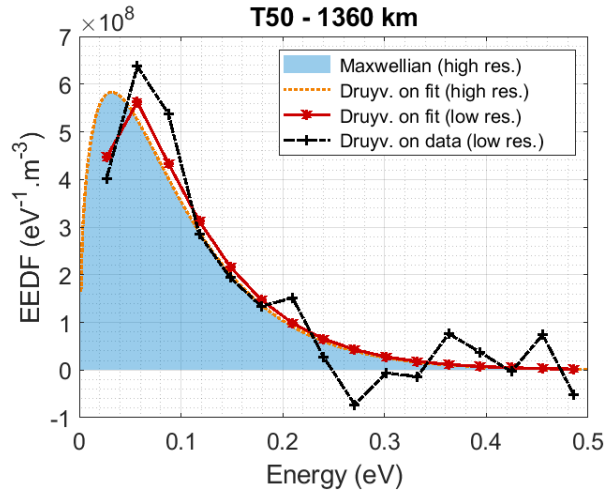
215

216 2.5.2 *EEDF: example with one population*

217 This section presents a simple case with one electron population (introduced in Figure S3 and
 218 S5(a)). Figure 4 compares the EEDF obtained by applying the Druyvesteyn method to the data
 219 points (Equation (6)), to the ‘Maxwellian’ EEDF computed with the fitted electron density and
 220 temperature (Equation (7)). They do not perfectly match (the maximum of the peak is shifted)
 221 because of the low resolution of the data points. Indeed, the Druyvesteyn method uses the second
 222 derivative of the current, which is highly distorted because of the low number of data points (e.g.
 223 the sharp initial increase is lowered by this effect).

224 To show this effect, the Druyvesteyn method is applied to the fit of the current. The EEDF obtained
 225 using a fitting curve at high resolution (> 200 points per peak) superimposes very well with the
 226 ‘Maxwellian’ EEDF. On the other side, the EEDF obtained using a fitting curve with the resolution
 227 of the Langmuir probe data points (4-10 points per peak) matches well with the EEDF obtained
 228 from the data points. The EEDF obtained using the Druyvesteyn method on the Langmuir probe
 229 data points is therefore fairly well represented by a ‘Maxwellian’ EEDF if one takes the problem
 230 of low resolution into account.

231



232

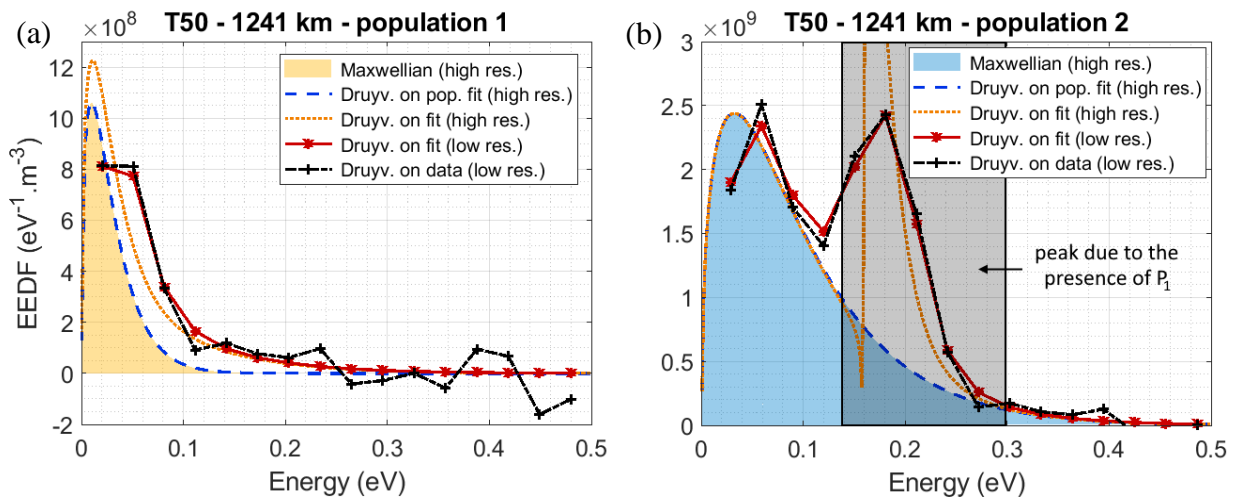
233 **Figure 4.** Example of EEDF obtained from Langmuir probe data with only one population using the
 234 Druyvesteyn method (dotted-dashed black line). Comparison to the EEDF obtained with the Druyvesteyn
 235 method applied to the fit at low resolution (red line), at high resolution (orange dotted line), and to the
 236 ‘Maxwellian’ EEDF from fitted n_e and T_e (blue area).

237

238 *2.5.3 EEDF: example with several populations*

239 In the case of data showing several populations, applying the Druyvesteyn method is less
 240 straightforward: the method requires one ‘plasma potential’ U_p , whereas the fit gives as much U_p
 241 as populations detected. Figure 5 shows the case of two populations. The Druyvesteyn method is
 242 applied to the data points using the U_p potential from (a) the first population and (b) the second
 243 population. In Figure 5b, the two population peaks appear in reverse order compared to the plot of
 244 d^2I/dU^2 in Figure 3a, because the x-axis is reversed ($E = -e \cdot \Delta U \propto -U_{\text{bias}} + U_p$).

245



246

247 **Figure 5.** Example of EEDF obtained from Langmuir probe data with two populations using the
 248 Druyvesteyn method: (a) for population 1; (b) for population 2. Comparison of the EEDF using the
 249 Druyvesteyn method on data points (dotted-dashed black line) to the EEDF obtained with the Druyvesteyn
 250 method applied to the fit at low resolution (red line), at high resolution (orange dotted line), to the fit of

251 only one population at high resolution (dashed blue line) and to the ‘Maxwellian’ EEDF from fitted n_e and
 252 T_e (area).

253

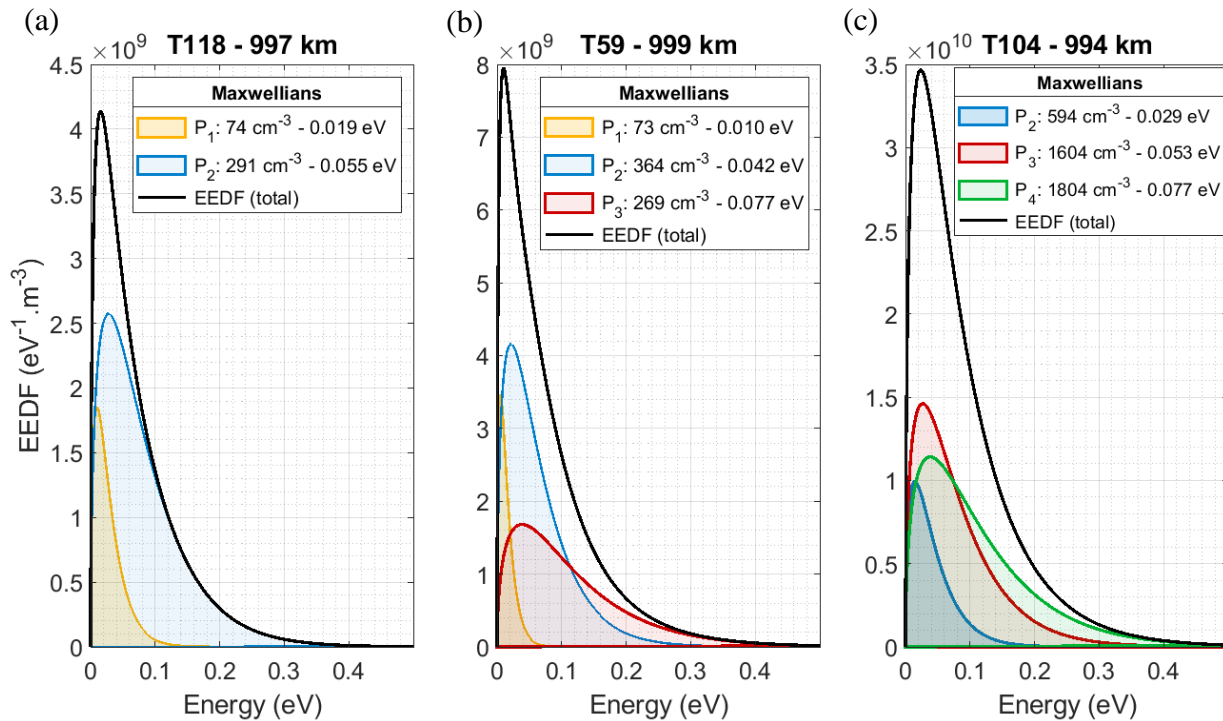
254 Figure 5 shows that in the case of several electron populations, the EEDF computed for one
 255 population with the Druyvesteyn method is disturbed by the other populations with close values
 256 of U_p . To observe this effect, the Druyvesteyn method is applied to the fit of the data points with
 257 the two populations (orange line), and to the fitted current corresponding only to one population
 258 (dashed blue line). Therefore, if one takes into account both the presence of nearby populations
 259 (supplementary peak at higher energy) and the effects of low resolution (shift of the main peak),
 260 the EEDF from data points can reasonably be modelled by a ‘Maxwellian’ EEDF (shaded area).
 261 An example with 3 populations is given in Supporting Information Figure S6.

262

263 *2.5.4 Diversity of EEDF combinations for the different populations*

264 The ‘Maxwellian’ EEDF of the electron populations are compared in Figure 6. As mentioned in
 265 Section 2.5.1, the area under each EEDF corresponds to the electron density of each population
 266 and the position of the maximum of the EEDF is related to the electron temperature.

267 Figure 6 shows the variability of the electron distribution (i.e. the changes in electron populations)
 268 for different flybys. It illustrates three very different cases obtained at ~1000 km altitude, which
 269 are representative of the three flyby groups (G1, G2 and G3) presented in details below, in Section
 270 3.1.



271

272 **Figure 6.** EEDF obtained from Maxwellian populations, at ~1000 km altitude for the flybys: (a) T118
 273 (group G1); (b) T59 (G2); (c) T104 (G3).

274 The first case (from the group G1) shows two populations (named P_1 and P_2). The area (and so the
 275 electron density) of P_2 dominates P_1 . The second case (G2) has one additional population (P_3). The
 276 area of P_2 and P_3 are equivalent and higher than the area of P_1 . We observe that P_3 distribution is
 277 in average at higher energy than the distribution of P_2 : its electron temperature is higher. Finally,
 278 the group G3 shows still another population (P_4) and P_1 becomes negligible compared to the others.
 279 P_3 dominates P_2 in density. P_4 characteristics vary with altitude: it can be denser than the others,
 280 and it is usually hotter.

281

282

283 3 Results and discussions

284 3.1 Variation of the electron populations with altitude and Solar Zenith Angle (SZA)

285 3.1.1 Variation with altitude

286 Voltage sweeps evolve during a flyby. The number of observed peaks in the second derivative of
 287 the current (d^2I/dU^2) varies with altitude. Therefore, the number of electron populations (and
 288 consequently the electron distribution) changes with altitude for a given flyby. We focus on the
 289 part of the ionosphere below 1200 km. The Langmuir probe took measurements at these altitudes
 290 at the occasion of 57 flybys.

291 The curves of d^2I/dU^2 as a function of the altitude obtained from the 57 flybys allow to easily
 292 classify Titan flybys in three groups. Each group has a different number of electron populations,
 293 with different characteristics. They are described in Table 1 and examples of profiles for the three
 294 cases are shown in Figure 7. All the profiles have similar d^2I/dU^2 curves around 1250-1200 km,
 295 showing usually three peaks. However, this curve evolves differently with altitude in the three
 296 cases. At lower altitude, in all cases, there is a main hump formed either by one large peak, two or
 297 three peaks (further named P_1 , P_2 , P_3 for clarity). In addition, for the profiles of the group G3, a
 298 small hump detached from the main one (P_4), at higher voltage, is observed below $\sim 1200 - 1150$
 299 km altitude.

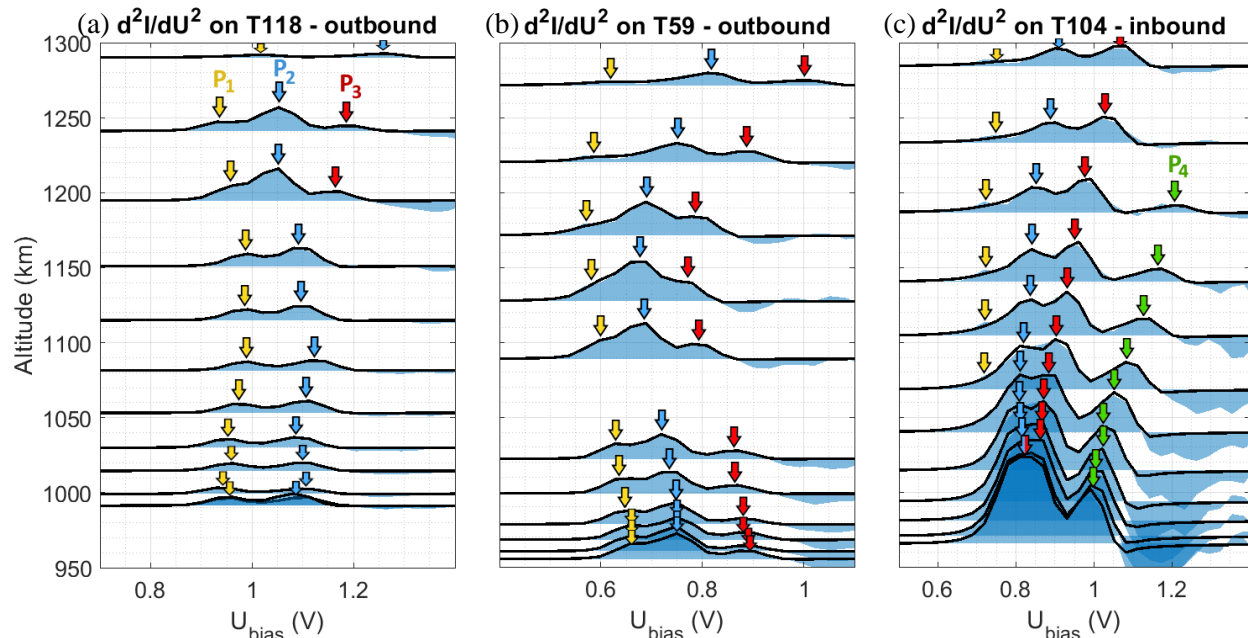
300

301 **Table 1.** Definition of the 3 flyby groups and their corresponding flybys. The flybys studied in details in
 302 Figure 7 and Section 3.2 are indicated in bold.

Name of the flyby group	Characteristics of d^2I/dU^2 at lower altitude	Flybys (T#)
G1	2 separated peaks	21, 25-28, 55, 118-119
G2	3 peaks	5, 16, 46, 50, 56- 59 , 65, 117, 121
G3	1 large peak (or 2 close) + 1 further, at higher U_{bias}	17, 20, 23, 39-43, 47-48, 51, 83-88, 91-92, 95, 100, 104 , 106-108, 113, 126
G1/G2	with different characteristics on inbound and outbound	29-30, 32, 120
G2/G3		18-19, 36, 49, 61, 70-71

303

304



305
 306 **Figure 7.** Examples of d^2I/dU^2 profiles with altitude: (a) T118 (from G1), (b) T59 (G2) and (c) T104 (G3).
 307 The second derivative of the electron current from Langmuir probe data (blue area) is superimposed to
 308 d^2I/dU^2 from the fit (black line). The scaling of d^2I/dU^2 is the same for all the plots. Arrows indicate the
 309 peaks corresponding to the 4 populations.

310

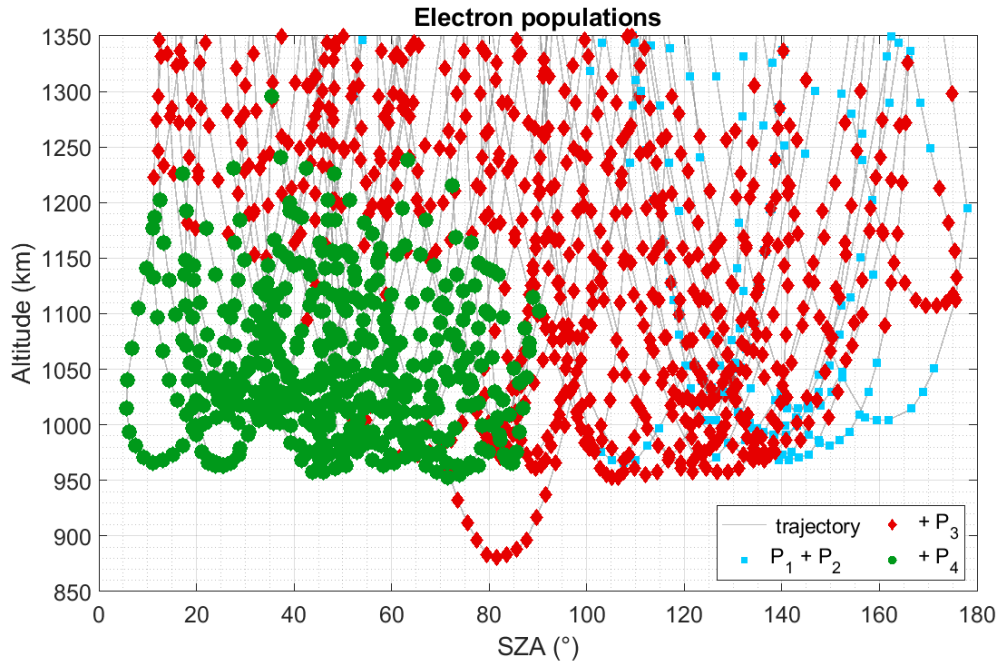
311 3.1.2 Variation with Solar Zenith Angle (SZA)

312 The detection of populations P₃ and P₄ are strongly dependent on the Solar Zenith Angle (SZA).
 313 Figure 8 shows the repartition of the electron populations with altitude and SZA in the case of 57
 314 Cassini flybys. The population P₄ appears always below ~1200 km and at SZA < 80-90° (such
 315 flybys belong to the group G3), and the cases without a P₃ population at lower altitude (group G1),
 316 are observed only on the nightside, at high SZA (>~120°).

317 The distribution of the 57 flybys in three groups is then closely correlated to their SZA. The group
 318 G1 corresponds to flybys on the far nightside (SZA >~120°), G2 to flybys on nightside close to
 319 the terminator, and G3 to dayside (SZA < 80-90°).

320 In conclusion, the variation with altitude and SZA of the detected peaks of d^2I/dU^2 can be
 321 schematized as in Figure 9. Each peak is attributed to an electron population among P₁, P₂, P₃ and
 322 P₄. At ~1200-1300 km, d^2I/dU^2 graphs are very similar at all SZA, with three populations (P₁, P₂,
 323 P₃). Below 1200 km, d^2I/dU^2 varies differently depending on SZA: (G1) on the far nightside (SZA
 324 >~120°), P₃ disappears; (G2) close to the terminator, the three populations are kept at lower
 325 altitudes, with an increase of the area of the P₂ peak; (G3) and on dayside, P₂ and P₃ grow, P₁
 326 becomes negligible and P₄ appears. In some occasions, P₂ and P₃ peaks merge.

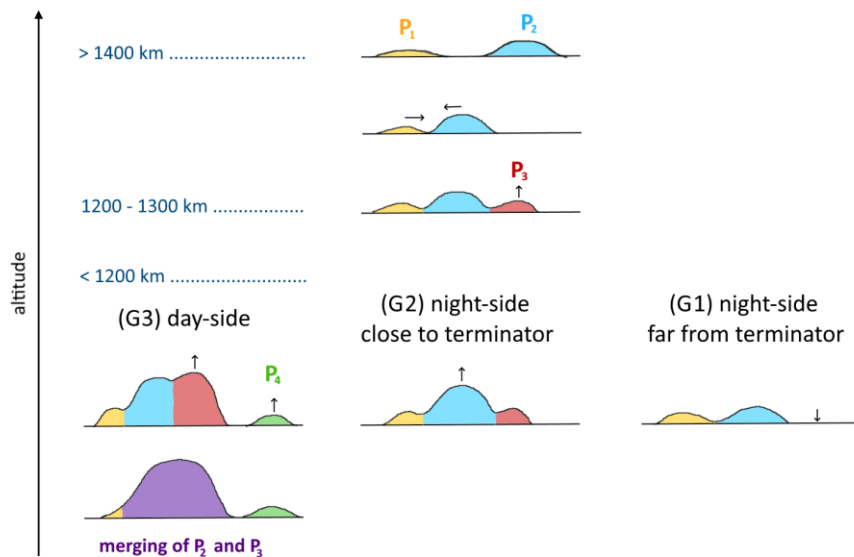
327



328

329 **Figure 8.** Detection of electron populations as a function of altitude and SZA, from 57 flybys. Blue squares
 330 represent sweeps with only populations P₁ and P₂, red diamonds show the presence of P₃, and green dots
 331 are for P₄.

332



333

334 **Figure 9.** Summary scheme of the evolution of d^2I/dU^2 peaks with altitude in the 3 cases: nightside far from
 335 terminator (G1), nightside close to terminator (G2) and dayside (G3). Small arrows indicate the evolution
 336 trends with decreasing altitude.

337

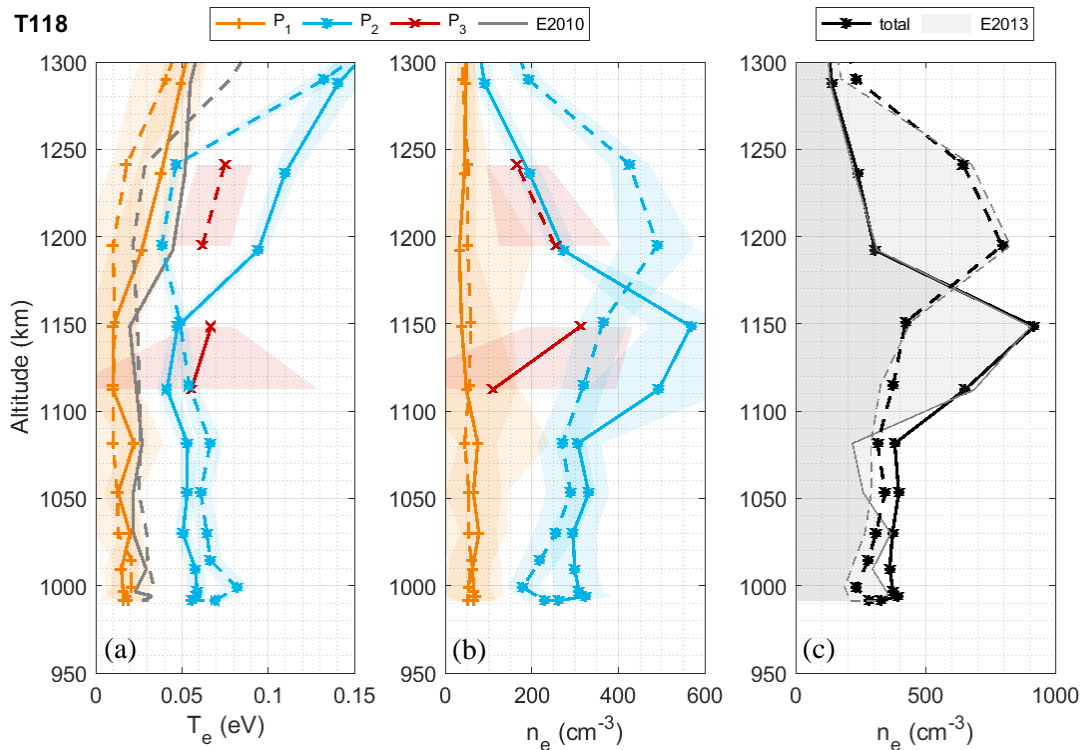
338 3.2 Electron densities and temperatures

339 The results on electron density and temperature are discussed separately for each of the 3 groups
 340 (G1, G2 and G3), in the following sub-sections (respectively 3.2.1, 3.2.2 and 3.2.3).

341 3.2.1 Nightside far from the terminator (group G1)

342 3.2.1.1 Typical altitude profiles

343 Figure 10 shows inbound (solid lines) and outbound (dashed lines) profiles of the electron density
 344 and temperature typical of the far nightside (G1). The confidence interval at 95% is indicated
 345 with shaded areas (see computation in Appendix C). The dominant population observed is P₂ (blue),
 346 with a rather constant temperature around 40-60 meV (460-700 K) below 1150-1250 km altitude.
 347 The density of this population peaks at an altitude varying between 1150 and 1250 km altitude.
 348 The population with the lowest U_p (P₁, orange) is very constant with altitude. Its density is low,
 349 less than 100 cm⁻³. Its temperature is around 10-20 meV (120-230 K), at the detection limit of the
 350 probe. In addition, a third population appears (P₃, red) at the ionospheric peak, when the total
 351 electron density exceeds 500 cm⁻³. It has a temperature higher than the other populations, around
 352 60-90 meV (700-1040 K).



353 **Figure 10.** Electron temperature (a) and density (b,c) profiles in the case of T118, an example of a G1 group
 354 flyby (far nightside); inbound (line) and outbound (dashed line); results for the different populations P₁, P₂
 355 and P₃ (colors). The fit confidence intervals at 95% are indicated in colored shaded area. The total density
 356 (sum of the densities of all the populations) is indicated in black. Comparison to Edberg et al. (2013, 2010),
 357 respectively noted E2013 and E2010 (grey).
 358

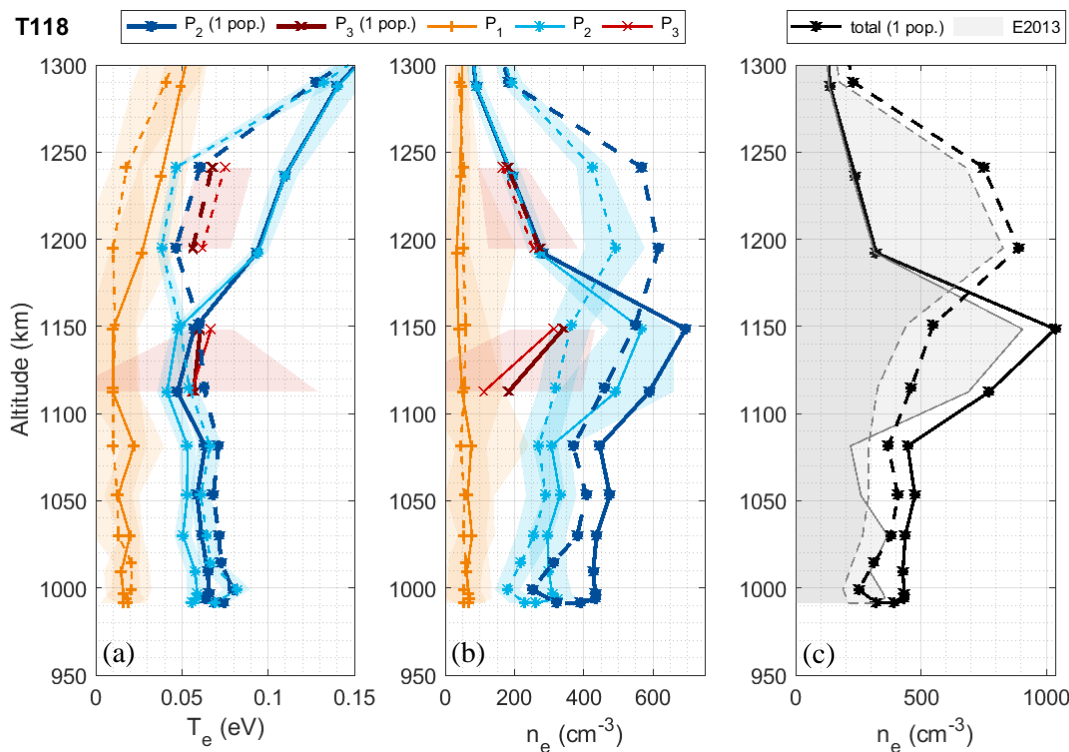
359

360 The total electron density obtained is consistent with previous measurements acquired with
 361 different methods (Ågren et al., 2009; Edberg et al., 2013; Garnier et al., 2009). The comparison
 362 of our fit to the density measurements by Edberg et al. (2013) serves as a validation tool. As for
 363 electron temperature, results are compared to a previous analysis (Edberg et al., 2010). This
 364 previous analysis usually gives an electron temperature between the ones found for P_1 and P_2 , and
 365 therefore sometimes colder than the dominant population (P_2) temperature. For instance, in the
 366 case of T118 shown in Figure 10, they obtained a temperature not representative of the main
 367 population of electrons (P_2). It shows that using several electron populations in the fitting of the
 368 sweeps significantly improves the analysis, since it attributes a temperature for each population,
 369 and consequently, the temperature of the dominant electron population can be found without
 370 ambiguity.

371

372 *3.2.1.2 Necessity to fit multiple populations*

373 Even if the population P_1 is not abundant, it is necessary to fit it separately from the main
 374 population P_2 to avoid a hot bias on the determination of the temperature of P_2 . For comparison,
 375 we studied the case where the current curve is fitted using only one population, as shown in Figure
 376 1a. The results are compared in Figure 11. Forcing only one electron population (P_2 , dark blue)
 377 overestimates the temperature of the dominant population (P_2 , light blue) by ~ 0.01 eV (~ 120 K).
 378 In addition, the total electron density increases of $\sim 10\%$ and is no longer consistent with the density
 379 measured by Edberg et al. (2013).



380

381 **Figure 11.** Same as Figure 10, superimposed to the T_e and n_e profiles obtained with only one population to
 382 fit P_1 and P_2 when their potentials are close enough (i.e. below 1200 km for inbound, and below 1300 km
 383 for outbound).

384

385

3.2.1.3 Discussion on the origin of P_1 and P_2

386 On the nightside far from the terminator, ionization is not governed by solar photons, but by
 387 energetic particles coming from the magnetosphere (Ågren et al., 2007; Cravens et al., 2008). We
 388 therefore assume that the dominant electron population (P_2) is the bulk of thermalized electrons
 389 initially formed by energetic magnetospheric particles.

390 The other population present at all altitudes, P_1 , is certainly due to electrons emitted by the nearby
 391 probe boom, from collisions with energetic particles. Such electrons are created on the nearby
 392 surfaces, they have low energy and are easily caught back. Therefore, P_1 corresponds to the
 393 population with the lower potential U_p .

394 P_3 is discussed in the following sections, as it is observed in higher quantities in groups G2 and
 395 G3.

396

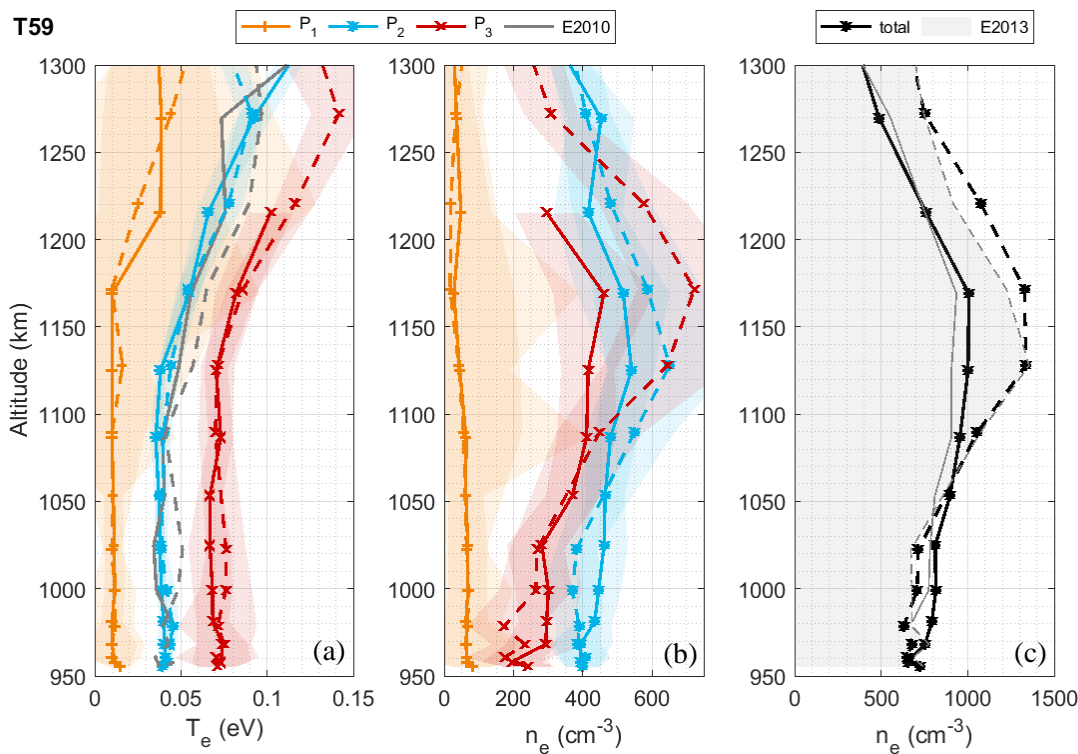
397

3.2.2 Nightside close to the terminator (group G2)

398

3.2.2.1 Typical altitude profiles

399 Flybys on the nightside close to the terminator ($\sim 90^\circ < \text{SZA} \sim 140^\circ$) show the presence of the
 400 third population at all altitudes (see Figure 12).



401

402 **Figure 12.** Same as Figure 10, in the case of T59, an example of a G2 group flyby (nightside close to the
 403 terminator).

404

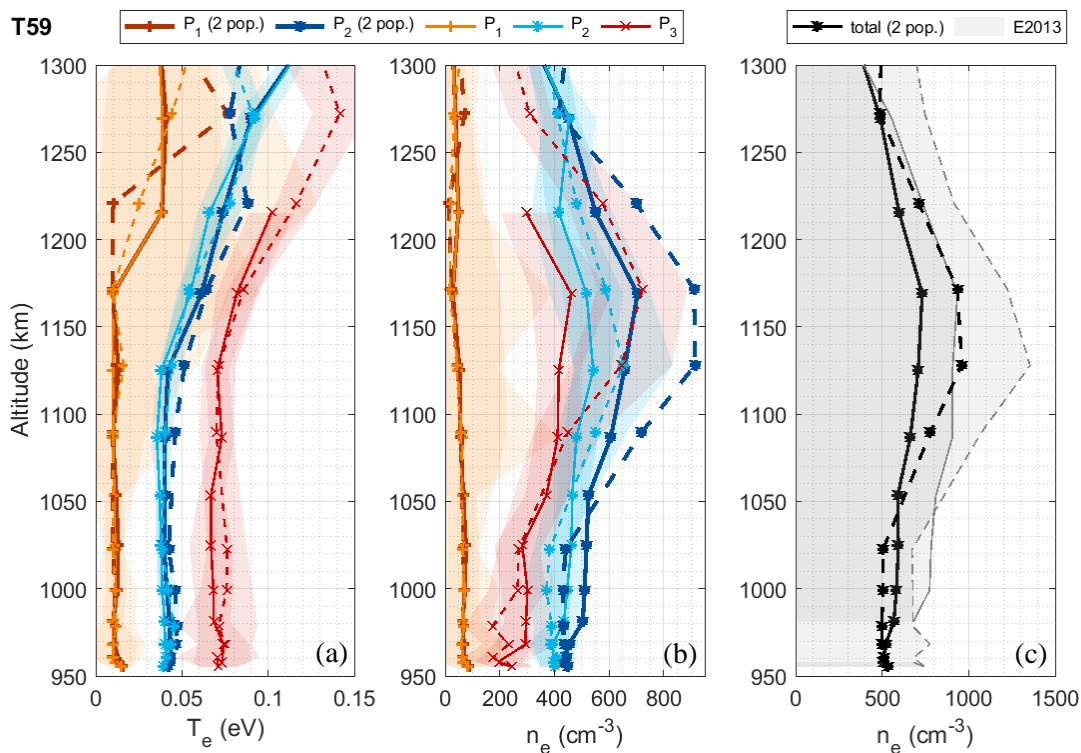
405 The total electron density is globally higher than for G1 flybys (far nightside), which is expected
 406 because of the closer influence of photoionization on dayside (Ågren et al., 2009). The
 407 temperatures observed for the three populations are similar to the ones of G1 flybys: P₁ below 20
 408 meV (~230 K, orange), P₂ generally between 30 and 50 meV (350-580 K, blue) and P₃ at 60-80
 409 meV (700-930 K, red).

410

411 *3.2.2.2 Necessity to fit multiple populations*

412 The addition of the third population (P₃) does not disturb the fitting of the two first populations.
 413 Besides, it is necessary to include it to obtain a total electron density similar to Edberg et al. (2013).
 414 This effect is showed in Figure 13. It compares the results obtained in Figure 12 with results of a
 415 fit that does not include the population P₃, as plotted in Figure 2 (a). Then, the temperatures
 416 obtained for P₁ and P₂ are almost unchanged, but the total electron density decreases of 25%.

417



418

419 **Figure 13.** Same as Figure 12, superimposed to the T_e and n_e profiles obtained for P₁ and P₂ when P₃ is not
 420 fitted.

421

422 *3.2.2.3 Discussion on the origin of P₃*

423 The fact that P₃ is observed on dayside (G3) but not on the far nightside (G1), suggests that it is
 424 due to the efficient photo-ionization processes happening on the dayside, whose influence is

425 extended by transport as far as the nightside close to the terminator. However, one should also
 426 consider a possible effect of the active ion chemistry happening in these regions on the
 427 characteristics of the electron population P_3 . In particular, the ionosphere environment on the
 428 nightside close to the terminator is enabling the growth of large ions, which is otherwise disrupted
 429 under direct extreme UV fluxes (Shebanits et al., 2017b, 2017a; Wellbrock et al., 2019).

430

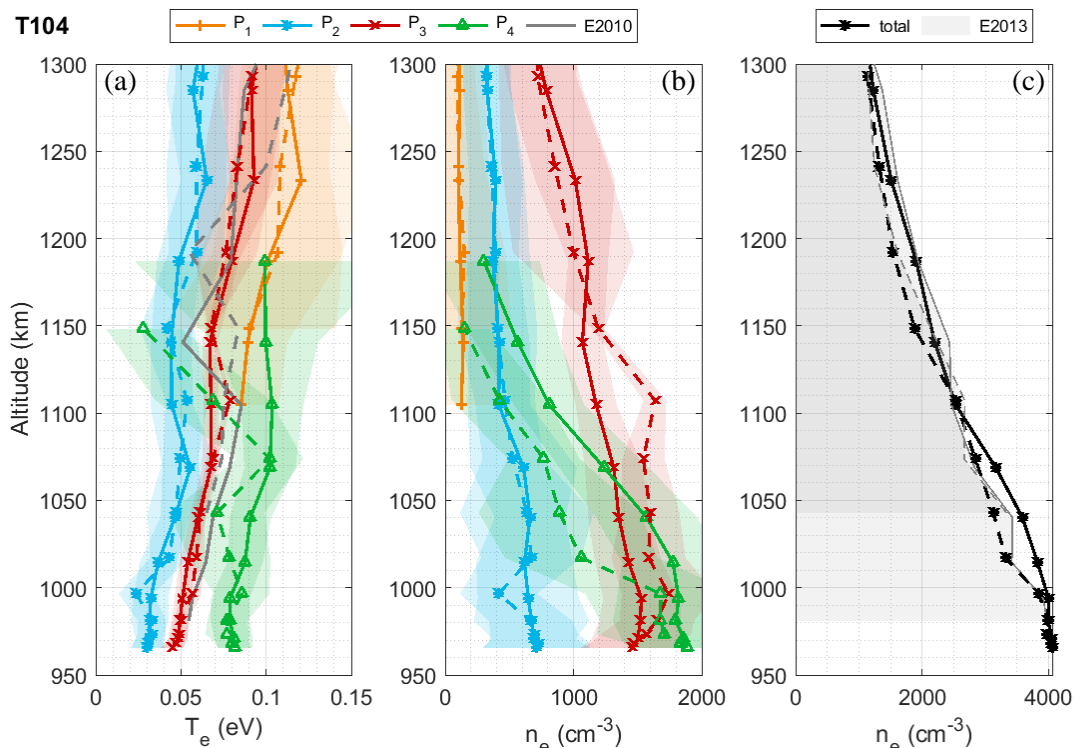
431

432 **3.2.3 Dayside (group G3)**

433 **3.2.3.1 Typical altitude profiles**

434 On dayside, a new population (P_4) appears in the LP sweep data at a potential U_P higher than for
 435 P_1 , P_2 and P_3 . Its temperature is generally higher than for the other populations, up to 0.1 eV (~1160
 436 K, green). This population appears only at altitudes below ~1200-1150 km and its density increase
 437 with decreasing altitude. In some cases (T17, T20, T85, T88, T104, T108), it even becomes the
 438 dominant population below 1050-1000 km, as shown in Figure 14. Contrary to the constant
 439 profiles on the nightside, the temperatures of all the populations decrease slightly with altitude, of
 440 ~0.03 eV (~350 K) in 200 km.

441



442

443 **Figure 14.** Same as Figure 10, in the case of a T104, an example of a G3 group flyby (dayside).

444

445 *3.2.3.2 Necessity to fit P_4 and fusion of P_2 and P_3*

446 The electron population P_4 is often non-negligible and should always be taken into account when
 447 present. An example of the results obtained if P_4 is not fitted is given in Supporting Information
 448 Figure S7. The results are similar to Section 3.2.2.2: the (U_p , n_e , T_e) results for the other populations
 449 are not impacted, but the total electron density is underestimated by up to 30%.

450 In some cases, the fitting of P_2 and P_3 can be ambiguous, especially at lower altitudes. The use of
 451 two distinct populations is required to obtain a very good fitting (examples of sweeps are given in
 452 Supporting Information Figure S8) and is consistent across all altitudes (see Figure 7 for T104).
 453 Nevertheless, the fusion of P_2 and P_3 at lower altitudes in G3 flybys happens smoothly: at one
 454 point, fitting with two or three populations gives globally the same results: P_2 becomes negligible
 455 compared to P_3 . An example of the n_e and T_e profiles obtained when P_2 and P_3 are fitted by only
 456 one population at lower altitude is given in Supporting Information Figure S9. The total electron
 457 density stays globally the same, the temperature of the main population is not impacted and the
 458 population P_4 generally stays in the range of its large error bars.

459

460 *3.2.3.3 Discussion on the origin of P_1 and P_4*

461 Similarly to the nightside, P_1 electrons on the dayside are certainly emitted by the probe boom.
 462 However, on dayside, the photoemission is also possible. In this case, the emitted electrons
 463 observed are hotter than on nightside.

464 The population P_4 is only detected on dayside. We argue here that it is not an instrumental effect
 465 but rather due to dusty plasma:

466 - Energetic photons and particles can detach electrons from the surface of the spacecraft.
 467 Nevertheless, in the ionosphere the electrons are cold enough to prevent these spacecraft
 468 electrons to reach the Langmuir probe (Wang et al., 2015). Indeed, the Debye length in the
 469 ionosphere is always below 10.5 cm, far lower than the distance between the spacecraft and
 470 the Langmuir Probe (which is on a 1.5 m boom).

471 - The spacecraft motion cannot explain the presence of several electron populations. With
 472 energies from 0.02 to 0.08 eV in the ionosphere, the electrons of the various populations have
 473 a thermal velocity of 85 to 170 km/s, much larger than the spacecraft velocity (~6 km/s).
 474 Therefore, there should be no difference in the electron collection from all around the probe.

475 - The perturbation of the collected current by organic deposit on the surface of the probe is not
 476 likely. In theory, the complex organic chemistry happening in the ionosphere could possibly
 477 lead to the formation of a deposit on the surface of the probe during the 10-15 minutes long
 478 ionosphere pass. Such a film coating, depending on the surface coverage and dielectric
 479 properties, would induce the detection of several electron components in the sweeps. However,
 480 no indication of this has been observed when comparing the sweeps ‘down’ and ‘up’ (see
 481 Section 2.1, Appendix A and Supporting Information Figure S1). Additionally, the probe is
 482 cleaned between two flybys (see Section 2.1), and observations during the inbound and the
 483 outbound are very similar (in the case of flybys with inbound and outbound at similar SZA).

484 - P_4 is possibly due to a dusty plasma effect. Indeed, it is not predicted by current ionospheric
 485 models that do not include the effect of the charged dust grains or aerosols on the electron

486 populations. The fourth electron population is only detected in the regions where dusty plasma
 487 has been previously measured (Shebanits et al., 2016), this suggests the charged dust grains to
 488 be the cause, either as a source or a disruption of the ambient electrons. This possibility is
 489 investigated in paper II.

490

491

492 **4 Conclusions**

493 The re-analysis of the Langmuir probe data in Titan's ionosphere brought new insights on the
 494 behavior of the electrons in this environment.

495 The detailed analysis of the data revealed the presence of several electron populations, at different
 496 potentials, and with different electron densities and temperatures. We have shown that the second
 497 derivative of the electron current collected by the Langmuir probe during a voltage sweep is a
 498 useful tool to detect the presence of several electron populations, especially as it is linked to the
 499 electron energy distribution function (EEDF) (Druyvesteyn, 1930). With the evolution of the
 500 second derivative of the current with altitude we observed the evolution of the electron populations
 501 with altitude in three different conditions: far nightside (T118), nightside close to the terminator
 502 (T59) and dayside (T104).

503 Two populations (with the lower potentials) are present in nearly all conditions. The third
 504 population is not observed on the far nightside, and the fourth is detected on dayside below 1200-
 505 1150 km. We have investigated the fitting of the electron current curve with 2 to 4 populations
 506 with a systematic approach on all flybys that validated the presence of 2, 3 or 4 populations only
 507 depending on the altitude and the solar illumination. A rigorous testing on the number of fitted
 508 populations shows that the fitting of all the detected populations (i.e. the whole electron
 509 distribution) is necessary to obtain a correct fit and retrieve the total electron density previously
 510 deduced from different methods (Ågren et al., 2009; Edberg et al., 2013; Garnier et al., 2009).

511 We suggested possible origins for the four populations:

- 512 - P₁ electrons, with the lowest potential and a low density, are emitted by the probe boom;
- 513 - a likely cause for the P₂ electrons, found even on the far nightside, is the thermalization of
 514 magnetospheric electrons;
- 515 - P₃ electrons, not present on the far nightside, are likely to be related to photo-ionization;
- 516 - and P₄ electrons, observed at lower altitudes on dayside, are plausibly linked to dusty
 517 plasma effects.

518 These four populations are studied in more details in paper II that performs a complete
 519 investigation on all the Cassini Langmuir probe dataset in the ionosphere of Titan.

520

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522

523 **Acknowledgments and Data**

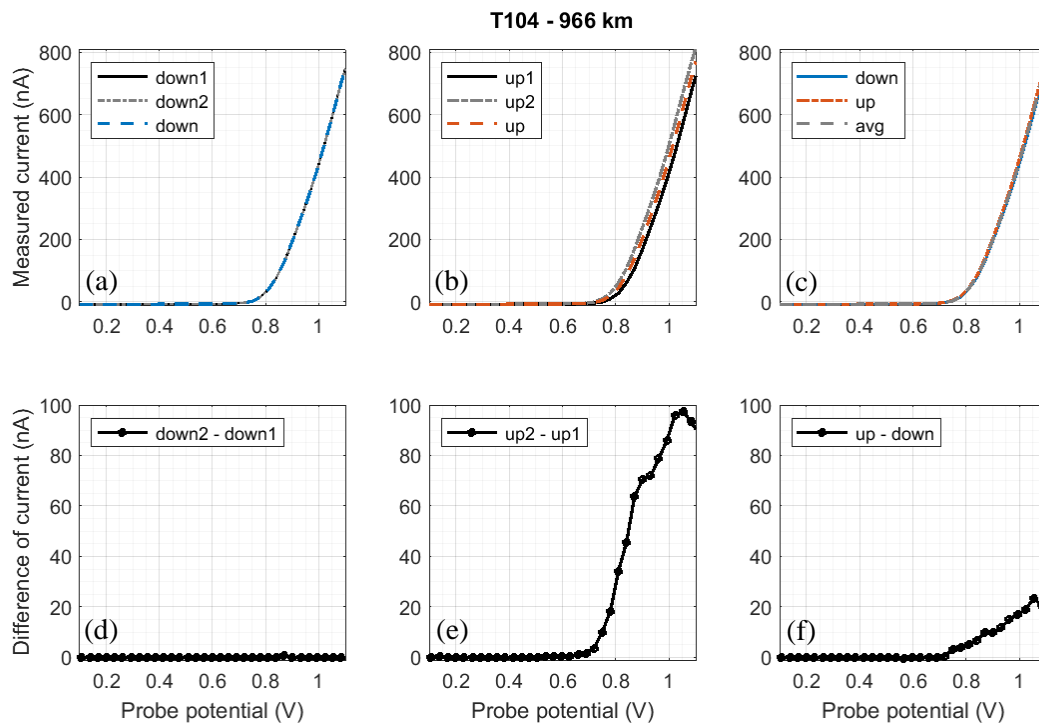
524 The Swedish National Space Board (SNSB) supports the RPWS/LP instrument on board Cassini.
 525 A.C. acknowledges ENS Paris-Saclay Doctoral Program. A.C. is grateful to Anders Eriksson,
 526 Jean-Pierre Lebreton, Erik Vigren and Ronan Modolo for fruitful discussions on this project. O.S.
 527 acknowledges funding by the Royal Society grant RP\EA\180014. N.J.T.E. was funded by the
 528 Swedish National Space Board under contract 135/13 and by the Swedish Research Council under
 529 contract 621-2013-4191. N.C. acknowledges the financial support of the European Research
 530 Council (ERC Starting Grant PRIMCHEM, Grant agreement no. 636829).

531 All Cassini RPWS data are archived in the Planetary Data System (PDS) Planetary Plasma
 532 Interaction (PPI) node at <https://pds-ppi.igpp.ucla.edu> on a pre-arranged schedule.

533
 534

535 **Appendix A.**

536 We investigated the reproducibility of the measurements with the two voltage sweeps (named
 537 ‘down’ and ‘up’), and the double measurements at each voltage step (resp. ‘down1’-‘down2’ and
 538 ‘up1’-‘up2’). Figure A1 shows the comparison.



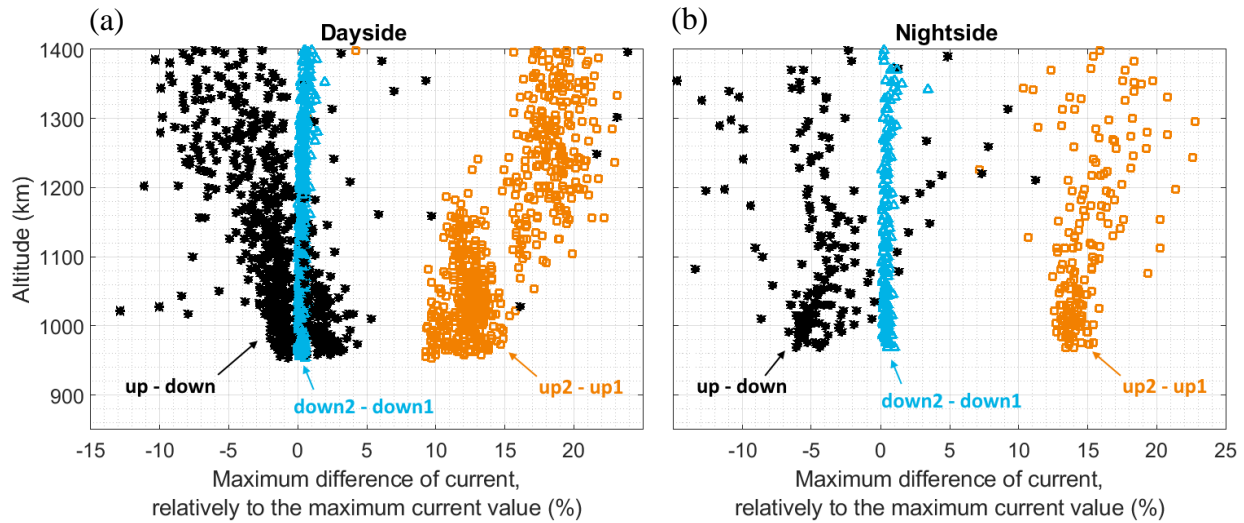
539 **Figure A1.** Raw data of the acquisition of a LP sweep. Left: data from the decreasing phase: (a) first point
 540 acquired (‘down1’), second point acquired (‘down2’), the average of both (‘down’) and (b) their difference
 541 (‘down2 – down1’). Middle: the same for the increasing phase, respectively (b) and (e). Right: (c) the
 542 average for the decreasing and increasing phases, the average of both (‘avg’) and (f) their difference (‘up –
 543 down’). From a measurement at ~966 km, during the Titan flyby T104.

544
 545

546 The two data points taken at a same voltage step during the decreasing voltage phase ('down1'
 547 and 'down2') are always very close to each other: the current stabilizes quickly at after each
 548 voltage step. However, during the increasing voltage phase ('up1' and 'up2'), the current continues
 549 to increase between the two measurements: the current takes longer to stabilize, especially in the
 550 strongly varying exponential parts of the sweep.

551 Figure A2 shows the variations 'down2 - down1', 'up2 - up1' and 'up - down' with altitude for
 552 26 flybys on dayside and 8 flybys on nightside far from the terminator. In each case, we selected
 553 the largest difference of current and the maximum of the averaged current in the voltage range
 554 $[Up1 - 0.7, Up1 + 0.3]$, $Up1$ being the plasma potential of the first population (it is located at the
 555 beginning of the increase of the current and is more precisely defined below). Figure A2 shows
 556 their ratio (difference / average) as a function of altitude. In all cases, the difference 'down2 -
 557 down1' (blue triangles) is very small, as opposed to 'up2 - up1' (orange squares) that ranges from
 558 9 to 23%. The difference 'up - down' (black stars) is often negative, and inferior to 10% in absolute
 559 values.

560 The difference between 'up1' and 'up2' shows that the collected current is not stabilized, and
 561 increases between the acquisition of the two points on a same voltage step. On nightside flybys
 562 (Figure A2b), the difference 'up2 - up1' varies smoothly with altitude, while on dayside flybys
 563 (Figure A2a) a sudden change in the difference is always observed between 1100 and 1200 km.



564
 565 **Figure A2.** Maximum differences of the current ('down2 - down1', 'up2 - up1' and 'up - down') in the
 566 voltage range $[Up1 - 0.7, Up1 + 0.3]$ as a function of altitude. The maximum differences are divided by the
 567 maximum of the averaged current to facilitate the comparison at different altitudes. (a) Flybys on dayside.
 568 (b) Flybys on nightside, far from the terminator.

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574 **Appendix B. Algorithm to fit the voltage sweeps with several populations**

575 To constrain the fitting of voltage sweeps in the case of several electron populations, the following
576 procedure is used:

577 1/ detection of the increase of the current (generally above 0.8 nA) and of the saturated part
578 (U_{lim});

579 2/ search for peaks in the second derivative of the current (d^2I/dU^2) in the voltage interval
580 defined in 1/;

581 3/ selection of the part of the voltage sweep (I_1) with a voltage inferior to the potential
582 corresponding to the minimum of d^2I/dU^2 between the two first peaks (or $< U_{lim}$ if there is only
583 1 population);

584 4/ fit of the current curve for the first population with Equations (2) and (5) in the reduced
585 voltage interval I_1 ;

586 If there is more than 1 population:

587 5/ selection of the part of the curve (I_2) with a voltage inferior to the potential corresponding
588 to the minimum of d^2I/dU^2 between peak 2 and peak 3 (or $< U_{lim}$ if there are only 2
589 populations);

590 6/ fit of populations 1 and 2 with two set of Equations (2) and (5) in the reduced voltage
591 interval I_2 , the initial parameters for the fit of the first population being given by 4/;

592 If there are more than 2 populations:

593 7/ selection of the part of the curve (I_3) with a voltage inferior to the potential corresponding
594 to the minimum of d^2I/dU^2 between peak 3 and peak 4 (or $< U_{lim}$ if there are only 3
595 populations);

596 8/ fit of populations 2 and 3 with two set of Equations (2) and (5) in the reduced voltage
597 interval I_3 , the initial parameters for the fit of population 2 being given by 6/. The contribution
598 of population 1 is beforehand removed, based on the fit results in 6/;

599 If there are more than 3 populations:

600 9/ selection of the part of the curve (I_4) with a voltage inferior to U_{lim} ;

601 10/ fit of populations 3 and 4 with two set of Equations (2) and (5) in the reduced voltage
602 interval I_4 , the initial parameters for the fit of population 3 being given by 8/. The contributions
603 of populations 1 and 2 are beforehand removed, based on the fit results in respectively 6/ and
604 8/;

605

606

607

608 **Appendix C. Confidence intervals for fit results**

609 The parameters fitted are not directly (U_p, n_e, T_e), but ($U_p, I_0, \beta = 1/T_e$), with T_e the electron
610 temperature in electron volt. The confidence intervals for the last three parameters are obtained at

611 95%. The standard deviation is then easily deduced for U_P and T_e . Concerning n_e , the standard
 612 deviation (σ_{n_e}) is obtained by the following equation, derived from Equation (3) applied to
 613 electrons:

$$\sigma_{n_e} = \left(\frac{\sqrt{2\pi m_e}}{A_{LP} e^{3/2}} \right) \times \left(\sigma_{I_0} \cdot \sqrt{\beta} + I_0 \cdot \frac{\sigma_{\beta}}{2\sqrt{\beta}} \right) \quad (C-1)$$

614 with I_0 and β obtained by the fit, and σ_{I_0} and σ_{β} their standard deviations.

615

616

617

618 **Appendix D. Equation linking the EEDF to the second derivative of the current (Druyvesteyn**
 619 **method)**

620 The equation for the electron velocity distribution as function of the second derivative of the
 621 electron current is given by the equation (3) in Druyvesteyn (1930):

$$\mathcal{V}(\Delta U) = \frac{4 m_e}{A_{LP} e^2} \cdot \Delta U \cdot \frac{d^2 I_e}{d\Delta U^2} \quad [(m \cdot s^{-1})^{-1} \cdot m^{-3}] \quad (D-1)$$

622 Electrons with a speed between v and $v + dv$ have energies between E and $E + dE$, therefore:

$$\mathcal{V}(v) \cdot dv = EEDF(E) \cdot dE \quad (D-2)$$

623 The derivative of the speed with respect to energy is given by:

$$E = \frac{1}{2} m_e v^2 \quad \Rightarrow \quad \frac{dv}{dE} = (2m_e E)^{-\frac{1}{2}} \quad (D-3)$$

624 Therefore, we obtain the EEDF by dividing the electron speed distribution by $\sqrt{2m_e E}$, with
 625 $E(\Delta U) = -e \cdot \Delta U$:

$$EEDF_{Dr}(\Delta U) = \frac{2\sqrt{2}}{A e^2} \sqrt{\frac{m \cdot (-\Delta U)}{e}} \frac{d^2 i}{d\Delta U^2} \quad [J^{-1} \cdot m^{-3}] \quad (D-4)$$

with $n_e = \int_0^{+\infty} EEDF_{Dr}(E(\Delta U)) \cdot dE$

626

627

628

629

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