Electron density and core temperature properties in the innermost Saturn’s magnetosphere from HF radio measurements on Cassini

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Abstract.

We analyze the large-scale structures of electrons in Saturn’s inner magnetosphere equatorial plane, from 2.8 to about 10 Saturnian radii ($1 R_S = 60330$ km).

The electron total density and core temperature are obtained using the quasi-thermal noise spectroscopy method, based on the power spectra measurements acquired with the Cassini/Radio and Plasma Wave Science (RPWS) instrument around the local plasma frequency from July 2004 to May 2012.

The results reveal the existence of two regions. An inner region around Enceladus orbit (3-5 $R_S$) is characterized by a high variability of the electron density, an increasing core temperature profile ($\propto R^{2.7}$) and a strong correlation of the density and temperature. An outer region, beyond 5 $R_S$, is characterized by a decrease of the density ($\propto R^{-4.19}$) and a slight decrease of the core temperature with distance from the planet ($\propto R^{-0.3}$). In the outer region, we identified a local time asymmetry of both the density and the temperature: higher core temperatures are observed in the nightside while higher densities are observed in the dayside. We finally computed an analysis of the plasma scale height dependence $H_{pl}$ on radial distance by using orbits quasi-parallel to the equatorial plane. It results that the $H_{pl}$ profile evolves as $R^{1.53}$ inside Dione’s orbit and displays a bump between 7 and 8 $R_S$, which is consistent with the maximum of corotation lag identified at the same radial distances. We conclude that in the inner region highly dependent on Enceladus meteorology, the electrons efficiently gain energy through thermalization with
the ions while in the outer region, electrons still undergo some heating and
are radially transported.
1. Introduction

Saturn’s inner magnetosphere is a very rich environment: it includes the ring system inside $3\ R_S$ with its ionosphere, the inner icy satellites, including Enceladus at $3.9\ R_S$, and the neutral gas torus. These elements provide material to the planet’s environment under different phases (solid, plasma, neutral gas) whose interactions affect the production, the energy and the sink of local plasma. This region is also characterized by the presence of very energetic particles from the radiation belts which hit the spacecraft, inducing a negative spacecraft potential.

Moncuquet et al. [2005] analyzed the quasi-thermal noise (QTN) measured by the high-frequency receiver of the Radio and Plasma Wave Science instrument (HFR/RPWS; Gurnett et al. [2004]) and derived the electron density and temperature parameters for the first Cassini orbit (i.e. SOI for Saturn’s orbit insertion). During this inclined pass which reached a periapsis at $1.3\ R_S$, they observed core electron temperatures from about 0.5 eV at the ring plane crossing, to 6 eV at $7\ R_S$, with densities ranging from 100 to 10 cm$^{-3}$. Sittler et al. [2006] computed the moments of electrons and ions from the low-energy plasma analyzer onboard Cassini, for the same orbit and confirmed the previous results. In another study, Persoon et al. [2005] determined electron density profiles for five equatorial orbits using the same technique. They identified a highly variable density profile inside $5\ R_S$. Later, Gurnett et al. [2007] organized those densities in function of the longitude system SLS4 [Kurth et al., 2007] and identified a sinusoidal dependence they interpreted as the evidence of the existence of a centrifugally driven two-cell convective instability. Schippers et al. [2008] derived the electron and temperature using the
CAPS/ELS (Cassini Electron Spectrometer) analyzer for one equatorial orbit (rev 24) from 5.4 to 20 \( R_S \) by adjusting an isotropic two-kappa model to the measured bimodal electron velocity distribution (i.e. thermal and suprathermal). They reported thermal electron temperatures ranging from 1 to tens of eV between 5 and 20 \( R_S \), which was confirmed by a statistical study Schippers [2009]. More recently, Schippers et al. [2012] updated the electron moments by considering the anisotropies. Their analysis allowed to distinguish three electron populations (instead of the two reported previously), the thermal being actually composed of a quasi-isotropic cold population of only a few eV and roughly constant with radial distance, and a warmer field-aligned population whose temperature increases with radial distance.

The identification of the radial offset of moon’s absorption microsignatures from the circular path of Saturn’s moons by Roussos et al. [2007] and then by Andriopoulou et al. [2012] led to the hypothesis of the existence of a noon-to-midnight electric field of about 0.01 to 1 mV/m. The evidence of such an electric field was confirmed by Thomsen et al. [2012] who reported and listed all the day/night asymmetries identified in the plasma component properties to derive an estimate of the radial offset of the plasma drift path between the day and night sides.

In the present study, we first describe the method we used to derive the electron density and core temperature (Section 2). We then present the spatial organization of these parameters (Section 3) in radial distance, local time and altitude, to finally discuss and interpret the results in terms of constraints on the thermodynamics of the inner magnetosphere (Section 4).
2. Method

We use the power spectral density measured by the HFR/RPWS receiver onboard the Cassini spacecraft.

The QTN spectroscopy technique consists in measuring the in-situ electrostatic fluctuations of the ambient plasma due to the particle thermal motion. It relies upon a fully understood theory and passive measurements with a simple electric dipole antenna and a sensitive receiver covering the range around the local plasma frequency [Meyer-Vernet and Perche, 1989]. This noise is ubiquitous and generally weak, but may be detected by a sensitive and low-noise receiver at the ports of an electric antenna immersed in a plasma: at frequencies where it is dominant, it can be used to measure in situ the moments of the electron velocity distribution (EVD). The basic reason is that this noise can be formally calculated as a function of both the EVD and the antenna geometry. Therefore, conversely, the spectroscopy of this noise reveals the local electron properties. Usually, the adjustment of a power spectral density model to the measured spectral density allows us to determine density, temperatures, and other moments of the EVD with more or less accuracy, depending on the performances of the sensors and receivers and their adequacy to the surrounding plasma. The main limitation of the QTN spectroscopy is to require an antenna’s length longer than the local Debye’s length. On the other hand, the QTN method has the unique advantage of a detection cross-section much larger than the surface of the detector itself, ensuring a great sensitivity and a quasi-immunity to spacecraft perturbations. Accordingly, the electron moment derivation technique from the QTN analysis is, in many cases, alternative to the usual techniques using the electrostatic ana-
lyzers and so provides an highly reliable electron moment estimation [Meyer-Vernet et al. [1998], Moncuquet et al. [2009] for reviews].

On Cassini, where the spectral resolution in the plasma frequency band is poor (48 log-spaced channels from $\sim 3$ to 300 kHz) and the spectra are often polluted by Saturn’s emission in the highest frequency band and the strong magnetic field brings additional contributions to the electrostatic noise as Bernstein modes [Meyer-Vernet et al., 1993], it would be very difficult to perform a fitting of a very detailed QTN model to the observed spectra. However, following Moncuquet et al. [2005], we may process a simplified QTN spectroscopy, namely limited to the frequency peak detection and to the measurement of the minimum power level which arises upstream to the peak. While less efficient and accurate than a full fitting method of QTN, the main advantage of the method remains: it is very weakly sensitive to spacecraft potential and to photoelectrons perturbations.

In summary, the results shown here are limited to the determination of the two following electron parameters:

1. The electron density, which is easily deduced from a strong signal peak near the upper-hybrid resonance $f_{uh}$, so independently of any calibration: from the peak at $f_{uh}$, we get the plasma frequency $f_p = \sqrt{f_{uh}^2 - f_g^2}$, with $f_g$ the gyrfrequency known from MAG [Dougherty et al., 2004], and thus the electron density $n_e = \epsilon_0 m_e (2\pi/e)^2 f_p^2$. It is important to note that the accuracy on the density is only dependent on the spectral resolution of the receiver (which is admittedly not very good but enough for our purpose). Furthermore, the dipole antenna is generally short compared to the local Debye length $L_D$ along a whole Cassini’s orbit, and so accurate electron density can be only obtained
around the Cassini’s perikrones, i.e. typically until about 10-11 \( R_S \). Beyond this distance, the plasma peak fades out.

2. The core electron temperature, deduced from the minimum power level \( V_{\text{min}}^2 \) (thermal plateau) below \( f_{\text{th}} \): In strong magnetized environment (as Io plasma torus, Earth plasmasphere, magnetosphere of Saturn), the thermal noise is dominated by the gyromotion of the particles, so that the spectrogram often exhibits quasi-thermal electrostatic Bernstein modes which propagate perpendicularly to the magnetic field. However, the minimum voltage level below the plasma frequency can be computed similarly to the non-magnetized case when the plasma frequency is much higher than the gyrofrequency \( f_p \gg f_g \), and characterizes the cold electrons (core) of the ambient plasma (see Appendix A).

Some further details concerning the method by Moncuquet et al. [2005] are provided in the appendix B, as in particular the rejection for statistical sampling of spectra contaminated by the shot noise.

3. Electron distribution in the equatorial plane

3.1. Radial organization

In order to study the electron moment radial organization, we selected orbits with altitudes in the vicinity of the equatorial plane, i.e. \(|z| < 0.05 \ R_S\), which avoids any bias due to the variation in latitude. Figure 1 displays the equatorial density (panels a & b) and temperature profiles (panels c & d) from Saturn’s orbit insertion on July 2004 to May 2012, including 117 exploitable perikrones. It includes the moments derived from the analysis of 396 675 spectra. In the left panel, the profiles derived for each Cassini orbit are displayed in different colors. In the right panel, the parameters were organized
in radial distance and a median profile was determined using radial bins of width \(= 0.4\) \(R_S\) (overlaid in red). In the same panel, power law models are superimposed in color.

The equatorial density is observed to be highly variable inside of 5.5 \(R_S\) and peaks at Enceladus orbit. Beyond 5.5 \(R_S\), the density decreases with the distance according to a power law at a first approximation. This inner distance of 5.5 \(R_S\) is that for which the dispersion of the data around the median density value and the reduced chi-squared are minimum. The adjusted power law in function of the equatorial radial distance \(R\) is:

\[
\text{n}_e \propto R^{-4.19\pm0.04} \text{cm}^{-3} \quad \text{for} \quad 5.5 < R < 9 R_S 
\] (1)

It is worth noting that the power law fitting result is dependent on the inner distance from which we apply the regression. Indeed, the power index varies from -4.1 (closer to the source region) at \(R=5\) to -4.4 at \(R=6\). We observed that the resulting radial density profile is similar to the one derived by Persoon et al. [2005] based on the analysis of the five first equatorial Cassini perikrones.

The mean core electron equatorial temperature and the envelope of the whole dataset increases with distance until about 4.8 \(R_S\). The adjusted power law in function of the equatorial radial distance \(R\) is:

\[
T_c \simeq 0.03 R^{2.7\pm0.1} \text{eV} \quad \text{for} \quad 2.8 < R < 4.8 R_S 
\] (2)

Again, the adjusted power law index is dependent on the chosen interval limits, varying from 2.7 at 4.8 \(R_S\) to 2.3 at 5.2 \(R_S\). For comparison, we superimposed (with a light grey dashed line) the power law model adjusted to the proton temperature radial profile derived by [Sittler et al., 2006, Figure 15] for the Saturn orbit insertion (\(\propto R^{-2.5}\)) which is in agreement with the statistical analysis from [Wilson et al., 2008, Figure 8].
core electron temperature trend is very similar to the proton temperature, with absolute values somewhat lower by a factor of 2.

Beyond 4.8 $R_S$, the equatorial temperature is observed to slightly decrease with distance, it can be modeled by a power law:

$$T_c \simeq 3.3 R^{-0.3 \pm 0.1} \text{ eV for } 4.8 < R < 9 R_S$$

(3)

### 3.2. Density-Temperature correlation

Figure 2 displays the equatorial core electron temperature $T_c$ versus the density $n_e$, obtained from the analysis of 32 234 spectra in the 3-5 $R_S$ radial distance region for altitudes such that $|z|$ is lower than 0.025 $R_S$ (Left panel) and $|z|$ is comprised between 0.025 $R_S$ and 0.05 $R_S$. The median profile of the density-temperature relation is superimposed in red dots. On the basis of the median profile and the upper and lower envelope of the relation, we observe that the two quantities are strongly correlated at least for the low and intermediate densities (below 80 cm$^{-3}$) for the nearest equatorial data (left panel), and the correlation seems to be conserved beyond 80 cm$^{-3}$ for the slightly upper altitudes (right panel). The loss of correlation in the first dataset seems to be related to the decrease of the envelopes, characterized by an excess of lower temperatures with respect to the second dataset. We adjusted a correlation model $T_c \propto n_e^k$ for densities up to 80 cm$^{-3}$, superimposed in a solid blue line on the two panels of Figure 2). It results that the power law index $k \simeq$ is about 1.2 for the two datasets. Blue dashed lines are superimposed at 2.5 times lower and higher than the model. It results that the lower and upper envelopes of the correlation for altitudes 0.025 $< |z| < 0.05 R_S$ follow the same trend as the derived mean model.
3.3. Day-night asymmetry

Figure 3 displays the equatorial electron density and core temperature profiles in the dayside and nightside, respectively in yellow and blue (solid lines). The statistical sample is equivalent for the two local time sectors: 177 712 spectra in the dayside and 175 547 in the nightside. A clear day-night asymmetry is observed in both the density and the temperature: densities are higher in the dayside while temperatures are lower than in the nightside. Moreover, this day-night difference increases with radial distance, the dayside density reaching a factor of nearly 2 at 10 \( R_S \) while the temperature is about 30 % lower than on the nightside. We superimposed the dayside and nightside electron temperature model from Thomsen et al. [2012] (yellow and blue dashed lines), calculated through the numerical integration of the measured EVD up to 150 eV. While different in absolute values, the temperatures derived from the QTN analysis and from the charged particle analyzer display an analogous local time asymmetry. The reason of the difference in the temperature value of the two datasets is due to the fact that the QTN analysis method provides the temperature of the core electron population while the temperatures derived by Thomsen et al. [2012] include a larger set of electron populations (cold and warm, up to 150 eV).

3.4. Radial evolution of the plasma scale height

Some Cassini orbits display a portion of their trajectory quasi-parallel to the equatorial plane. Analyzing and comparing the radial evolution of the density of these off-equator passes at different altitudes gives a direct observation of how the scale height varies with the distance to the planet, within the mere assumption the plasma scale height is independent of the plasma/neutral gas torus filling state. This requires a normalization in
order to compare the density profiles measured at different epochs, so with different filling
states. We perform this normalization by computing a mean electron density at $5.5R_S$
for each orbit and also by fixing an arbitrary value for the plasma scale height at $5.5 \, R_S$
(see below for its definition).

Figure 4-a shows the normalized radial profile of the density of the following orbits
rev047, rev050, rev052, rev136, rev138 and rev139 which include time intervals at a quasi-
constant altitude (between $0.19 \, R_S$ and $0.6 \, R_S$ above or below the equatorial plane),
together with the density model in the equatorial plane derived in section 2 (power law
index of -4.19 beyond $R=5.5$).

From the selected profiles, we can then derive the plasma scale height $H_{pl}$ variation with
dipole $L$, considering a Gaussian distribution model of the density around the equator,

$$n_e(z, L) = n_e(0, L) \exp(-z^2/H^2_{pl}(L)) \quad (4)$$

This expression has been initially derived for describing the equatorial plasma confine-
ment due to the centrifugal force effects in Jupiter’s magnetosphere [Hill and Michel,
1976]. In Saturn’s inner magnetosphere, the centrifugal force is also dominant and as a
consequence, the ions are confined at the magnetic equator implying the development of
an ambipolar electric field which in turn confines the core electrons, i.e. Persoon et al.
[2009]. However, it is important to keep in mind that such a simple model of Gaussian
scale height confinement is only valid for small $z$ and assuming the plasma in thermal
diffusive equilibrium. We will return on these points further in the discussion. In this
section, we consider $H_{pl}$ as a pure observable defined by Eq.4, and we observe it on six
Cassini orbits with quasi constant and moderate altitude $z$. 
Figure 4-b displays the plasma scale height $H_{pl}$ so determined from 5.5 $R_S$ to about 11.5 $R_S$, for different orbits. Note that in Eq.4 the term $n_e(z, L)$ yields for normalized density and so includes the filling factor calculated with the arbitrary value $H_{pl}(5.5)=0.7 R_S$. We observe that the scale height radial profile behavior is similar for all the considered orbits, at least until 8 $R_S$ and except rev050 (the most distant from the equator at $z \simeq 0.6 R_S$).

The mean scale height (heavy black line in the figure) increases and reaches a maximum at about 7.3 $R_S$. Beyond this distance, the scale height decreases and reaches a plateau.

More precisely, we can distinguish three ranges from both sides of Dione’s and Rhea’s L-shells:

- Inside Dione’s orbit (from 5.5 to 6.2 $R_S$), the trend is similar from one orbit to the other (except rev050 where the observed scale height keeps roughly constant) and is consistent with a power law of index between 1.25 and 1.85, with an average of $\simeq 1.53$ (dashed line on the figure). So the confinement at low altitudes is well modeled by a gaussian distribution inside Dione L-shell. This result is in good agreement with the recent result from Persoon et al. [2013] who found $H_{pl} \propto L^{1.5}$. At higher altitudes, like for orbit rev050, the distribution may depart from the Gaussian model if the plasma is out-of-equilibrium (i.e. Lorentzian).

- Between Dione’s orbit and Rhea’s orbit (from 6.2 to 8.8 $R_S$), the scale height is bell-shaped, with increasing trend’s slope until 7.3 $R_S$, but we note a high variability of the scale height, especially on rev139, which exhibits a clear ”bump” in the density profile (4-a, cyan colored), where normalized densities reach larger values than expected at the equator with our model.
Beyond Rhea’s orbit, the mean scale height appears to be roughly constant, but this is statistically not significant since we have only two exploitable orbits at these distances (rev136 and rev138+rev047), which exhibit very different behaviors.

4. Discussion

In Saturn’s inner region (< 9Rs), we identify two regions distinguishable by a different density and core temperature behavior.

4.1. Density

The electron density peaks in the 3-5 Rs region, around Enceladus orbit (3.9 Rs), and the large dispersion suggests that the plasma source is highly variable in time. This density variability is most probably due to the presence of the icy satellite Enceladus. Indeed, plumes of water-rich gas and ice grains are venting from the moon’s south pole and are the origin of a narrow neutral gas torus around the moon which extends to a larger torus in the inner magnetosphere [Dougherty et al., 2006; Smith et al., 2010, and references therein]. The region around Enceladus then provides most of the material for the cold plasma production through photoionization of the neutral gas torus by the solar flux [Schippers et al., 2009], electron-impact ionization on the neutral gas (for electrons hotter than the ionization potential of the ambient neutral species), dust-dust interaction [Mann and Czechowski, 2005; Juhász and Horányi, 2002], electron injection from the ionosphere by field-aligned currents which develop because of the moon-magnetosphere coupling [Pryor et al., 2011].

Outside of 5 Rs, the radial density profile decreases according to a power law model with index n ≃ -4.2 as reported by Persoon et al. [2005]. The flux tube content η can be
approximated by:

$$\eta = \frac{n_e H_{pl}}{B}$$  \hspace{1cm} (5)

where the magnetic field B is dipolar in first approximation ($\propto R^{-3}$). Considering the upper and lower limits of the power law index of the density and plasma scale height models respectively determined in sections 3.1 and 3.4, we obtain that the resulting power law model for $\eta$ has an index varying from -0.15 to 0.75, which means that the flux tube content is globally constant in the region between $R=5.5$ and $R=9$. In a first approximation, this is indicative of a transport region, including minor plasma sources outwards.

4.2. Temperature

We observed that the core electron temperature in the inner Saturn’s magnetosphere ranges from less than 1 eV up to less than 10 eV, characterized by an increasing trend inside $5 \ R_S$ while it is slightly decreasing outside of this distance. Moreover, in the innermost region, the temperature is highly correlated with the density.

The core temperature value results from

1. the source mechanisms: these were mentioned in the previous subsection (4.1). The importance of these processes depends, among others, on the solar flux intensity, the hot electrons density and distribution.

2. the heating processes: the electrons may undergo heating through thermal equilibration by Coulomb collisions with warmer plasma components such as hot electrons or the ions. The thermalization rate $\nu^{el/\beta}$ between a core electron population and a plasma component $\beta$ is proportional to $(m_\alpha m_\beta)^{1/2}n_\beta/(m_e T_\beta + m_\beta T_c)^{3/2} \ s^{-1}$ which implies that the thermalization process is more efficient and faster with a denser and lighter plasma component.
3. the cooling processes: electrons may also undergo cooling through inelastic collisions with the neutral gas (electron-impact excitation) and the dust. Note that particle-wave interactions also yields to electron heating and cooling.

4. the radial transport: indeed, additional cooling or heating through the first and second adiabatic invariants conservation (respectively $\mu = E_{\perp}/B$ and $j = \int v ds$) is occurring during radial transport. In a dipolar magnetic field configuration dominated by radial transport, the radial dependence of the total temperature is expected to vary as $R^{-8/3}$.

First, In Saturn’s magnetosphere, evidence for photoionization was reported by Schippers et al. [2009]. This process creates electrons with energies from a few eV to tens of eV. The more energetic ones whose energy exceeds the ionization potential of the neutral species (essentially water-group neutrals with $E \approx 13$ eV in Saturn’s inner magnetosphere) are able to ionize the neutral cloud and yield to the production of cold plasma.

Then, it is expected that thermal equilibration of the core electrons in Saturn’s magnetosphere takes place with the hot electron populations (suprathermal electrons and photoelectrons), the dominant water-group ions $W^+$, and the protons $H^+$. First, the suprathermal hot electrons display a peak of density and temperature at $9 R_S$ [Schippers et al., 2008], both quantities decreasing drastically inward. Inside $5 R_S$, the calculated suprathermal densities were identified to be very low, below $0.01 \text{ cm}^{-3}$ at $4 R_S$ [Schippers, 2009] which means a factor at least 10000 much lower than the total electron density ($\approx 100 \text{ cm}^{-3}$). The photoelectron hot component, identified in the Enceladus orbit surroundings, is expected to strongly interact with the dense neutral material in the source region and its density is also estimated at low values compared to the core electron density, i.e.
below 0.1 cm$^{-3}$ at 3 $R_S$, negligible compared to the total density [Schippers et al., 2009]. Moreover, its temperature profile is observed to be rather constant in function of radial distance. Second, Sittler et al. [2006] determined the ion density and temperature profiles from the CAPS/IMS (Ion mass spectrometer) measurements during the first orbit of Cassini around Saturn (i.e. SOI, July 1 2004), using the integration method to derive the moments of the EVD, for radial distances as close as 3.5 $R_S$ up to 10 $R_S$. These initial results were then confirmed by a statistical analysis from Wilson et al. [2008], based on the ion moment determination in the 5-10 $R_S$ region by using the forward modeling method (adjustment of the measured EVD with a bi-Maxwellian model). A statistical analysis extended to radial distances up to 20 $R_S$ was then conducted by Thomsen et al. [2010], using the integration method. The perpendicular heavy ion temperature follows a power law with an index close to 2 while the proton corotation temperature profile was reported to follow a steeper trend, with a modeled power law index of 2.5 [Sittler et al., 2006] confirmed by [Wilson et al., 2008, Figure 8]. These studies concluded that the ion temperatures are in a fair agreement with ion pick-up processes yielding $T_{\text{ion}} \propto R^2$. As we previously noted out, the core electron temperature profile inside 4.8 $R_S$ ($\propto R^{2.7}$) follows a trend very close to the proton temperature profile derived and the absolute electron temperature values are lower than the proton temperature by a factor of about 2.

Important amounts of neutral gas and dust are released by Enceladus venting at 3.9 $R_S$. This material interacts with the ambient plasma through multi-phase interactions which are either a source of energy for the local plasma (charge exchange) or a source of cooling, such as the inelastic collisions of the cold core electrons with the neutrals.
(yielding excitation) and collisions with dust. Such cooling effects are expected where the density of dust and neutrals is maximum. Neutral and dust density peak at Enceladus orbit [Johnson et al., 2006; Kurth et al., 2006, respectively], yielding to maximum cooling effects around $3.9 \, R_S$. The quantification of these mechanisms is bad constrained up to date. Concerning heating or cooling through wave-particle interactions, no evidence of persistent or regular wave signatures in the inner magnetosphere was identified. We then expect this kind of interactions to be more sporadic.

Finally, evidence of radial transport in the inner magnetosphere, triggered by different mechanisms has been reported by several authors [Roussos et al., 2007; André et al., 2007]. In our analysis we concluded that the $5 - 9 \, R_S$ region, dominated by the dipolar magnetic field is consistent with a radial transport region. The observed electron core temperature profile is however less steep than the predicted trend.

In Figure 5, we compare the rates of radial diffusion from Barbosa [1993] ($\propto R^3$) and the total thermalization rate of the core electrons. It clearly appears that thermalization dominates inside $4.8 \, R_S$, essentially driven by the ions, whereas radial diffusion dominates beyond this distance. The transition location interestingly matches the distance where we identified a change in the character of the core electron temperature radial profile (displayed in Figure 1). We then conclude that core electrons probably undergo strong thermalization with the ions in the innermost magnetosphere (corroborated by the observed electron and ion temperature) while radial diffusion effects on the temperature starts to be effective as close as $4.8 \, R_S$. 
4.3. Density-Temperature correlation

We identified a strong correlation of the density and the temperature in the 3-5 $R_S$ region, precisely where the thermalization process dominates (see previous section). Such a correlation is consistent with a heating process whose efficiency is highly dependent on the total electron density, but also on the total ion density according to the quasi-neutrality property of the plasma. In consequence, enhanced electron density means enhanced ion density, and the ion-electron thermalization mechanism rate is precisely highly dependent on (proportional to) the neutral ion density.

We however observe that the correlation is lost for the strict equatorial values ($< 0.025 R_S$) when densities are higher than 80 cm$^{-3}$ while it is conserved for denser plasmas at slightly higher altitudes $0.025 < z < 0.05 R_S$. Indeed, a denser plasma is actually measured when the source activity (Enceladus venting) is enhanced, which means that an increasing amount of dust and neutral material is released from Enceladus into the magnetosphere, in the equatorial plane. Such an activity increases the cooling efficiency of the electrons with large equatorial pitch-angles. At higher altitudes, the measured electrons have a non-null parallel temperature and these then spend less time inside the densest region in neutral and dust species (i.e. the equatorial plane).

4.4. Day-night asymmetry

We identified a day-night asymmetry of the density and the temperature profiles. Such an asymmetry has previously been observed in a couple of other plasma parameters: the radial offset of the icy moons absorption micro-signatures [Roussos et al., 2007; Andriopoulos et al., 2012], the radiation belts intensities [Paranicas et al., 2010], the energy flux of the cold energy electrons [DeJong et al., 2011], the field-aligned currents [Schip-
pers et al., 2012] possibly related with the day-night asymmetric secondary auroral oval identified by Grodent et al. [2010], and in the ion temperature [Thomsen et al., 2012]. Andriopoulou et al. [2012] explained the radial offset of the moons micro-signatures as the result of the existence of a noon-to-midnight electric field which would be associated with a convection pattern driving particles outward on the dawn side and inward in the dusk side [Thomsen et al., 2012]. Recently, Wilson et al. [2013] measured the in-situ radial velocity of the ions and confirmed the presence of a drift velocity pattern consistent with the convective electric field which adds up to the corotational drift pattern. The asymmetry we identified in the density and temperature profiles of the core electron population is consistent with the previous observations and the direction of the expected noon-to-midnight electric field. Indeed, the direction of the electric field implies an offset of the nearly circular drift electron paths from night to day, which implies lower temperatures and higher densities in the dayside at the same equatorial distance.

4.5. Radial evolution of the plasma scale height

As shown in section 4, the behavior of the plasma scale height, defined from a Gaussian model of confinement, is well described by a power law as $R^{1.53}$ outside of the source region (i.e. 5.5 $R_S$) and below Dione’s orbit. Beyond this orbit, using this model is more questionable. [Hill and Michel, 1976] derived the following expression for the scale height:

$$H_{pl} = \sqrt{2kT_{i,\parallel}/3m_i\Omega^2}$$

(6)

where $T_{i,\parallel}$ is the parallel temperature of the ions and $\Omega$ is the corotational angular velocity. As stated by equation 6, the scale height highly depends on the parallel ion temperature. In Saturn’s magnetosphere case, the heavy water-group ions have the largest density
[Thomsen et al., 2010], we then expect this population to control the scale height. Wilson et al. [2008] and Thomsen et al. [2010] derived equatorial ion temperatures using the CAPS/IMS (Ion mass spectrometer) data using the forward modeling method (spectra adjustment with bi-Maxwellian distribution function models) and the integration method respectively. The temperature profile of the heavy ions $W^+$ displays an increase inside of $10 \, R_S$ and a flat radial profile beyond $10 \, R_S$ (Figure 8 in Thomsen et al. [2010]). Wilson et al. [2008] determined the anisotropic $W^+$ ion temperatures. Inside $R=10$, the $W^+$ perpendicular temperature is consistent with the pick-up temperature ($\propto R^2$) (Figure 7 in the referenced paper), probably modified by interactions between plasma species and/or wave-particle interactions, but the (lower) parallel temperature displays a different trend, with a trend steeper than $R^2$. This is consistent with the increase of the plasma scale height faster than $L$ as we determined from our analysis inside $R=7.3$.

Beyond $7.3$ and inside $R=10$, the scale height behavior displays a decreasing trend while the ion temperature is still crescent in this radial distance interval, albeit much more slowly than at smaller distance [Wilson et al., 2008]. The reason for this discrepancy may arise from the corotation lag. Indeed, Wilson et al. [2008] derived the azimuthal bulk velocity profile and found that it displays a maximum gap from strict corotation at $7.5 \, R_S$, where we precisely identified a maximum in the scale height. The apparent correlation between the corotation lag and the scale height can be interpreted as the consequence of a reduced centrifugal (then ambipolar) potential when corotation lag occurs, causing a reduction of the confinement of the plasma around the equator. Reasons for corotation lag are radial mass transport, loading of the plasma flux tubes (ion pickup), and collisions of the ions with the neutrals. The observed maximum in the scale height has however not
been identified in the previous studies by Persoon et al. [2006] and Thomsen et al. [2010] beyond 7.5 $R_S$. In these statistical studies, the plasma scale height was derived from the analysis of a large set of inclined orbits merged together. The data were organized along magnetic shells using the assumption of a dipolar magnetic field and the plasma is assumed to be strictly corotating. They found a strictly increasing trend for the scale height as far as 16 $R_S$ and does not display any bump at 7.5 $R_S$ as we identified from our study. The reason for the discrepancy may be that these studies are based on the merging of datasets measured during different plasma torus filling state conditions. This yields to compare, on a magnetic shell, data of a very different nature.

5. Conclusion

In conclusion, we determined the electron density and core temperature calculated from the quasi-thermal noise spectroscopy technique applied to the High Frequency Receiver of RPWS/Cassini in the inner Saturn’s magnetosphere for a period spanning from 2004 to 2012 inside 10 $R_S$. We showed that the region inside 3-5 $R_S$ is characterized by an important dispersion of the density values, mainly influenced by the variable activity of Enceladus. The core temperature follows an increasing trend, very probably due to the thermal equilibration with the protons and heavy ions. This region is characterized by a strong temperature-density correlation. Beyond 5 $R_S$, the density profile suggests radial diffusion whereas the nearly flat core temperature is intermediate between thermalization with the other plasma components and cooling induced by outward radial diffusion. The core electron moments display an asymmetry with local time consistent with a noon-to-midnight convective electric field. The analysis of the plasma scale height indicates that it is consistent with the previous results from Persoon et al. [2006] but we identified a new
feature, a bump between Dione and Rhea’s orbit consistent with a pronounced corotation lag in the region. Further analysis will include the analysis of the effects of the dust on the plasma and the determination of the hot electron component temperature through the analysis of Bernstein modes.

Appendix A: Calculating $T_c$ from the QTN minimum level

We mainly use the method applied by Moncuquet et al. [2005] on the SOI data. We take advantage of the fact that $f_g \ll f_p$ during the periods when $f_{uh}$ is detected, so the computation of the QTN minimum upstream $f_{uh}$ is roughly equivalent to its computation in an unmagnetized plasma [Meyer-Vernet and Perche, 1989, section 6.2.3]. Note however this equivalence stands only for computing the minima of the QTN level, which take place at the gyroharmonics, and not for the whole band noise level upstream $f_{UH}$, where the QTN may be enhanced by the ”QTN in Bernstein modes” between the gyroharmonics: that was exploited in Moncuquet et al. [2005] but is not done in the present paper.

Note also that we usually assume in planetary magnetospheres that the EVD can be modeled by a sum of two maxwellian electron populations (often called ”core + halo” distribution), and so we usually distinguish a cold and a hot population, but there is actually no need to assume a maxwellian core+halo in what follows (for the significance of temperature measurement -and of the ”core temperature”- in a non-Maxwellian plasma see i.e. [Moncuquet et al., 1995, section 4]). The QTN minimal level is then given in Moncuquet et al. [2005] as a function of the core temperature $T_c$ and (core) Debye length $L_D$ by:

\[ V_{min}^2 \approx \frac{8\sqrt{2m_e k_B T_c}}{\pi^{3/2} \epsilon_0 (1 + C_B/C_A)^2} \int_0^\infty \frac{F_V(kL)k L_D^2}{[k^2 L_D^2 + 1]^2} dk \]  

(A1)
all in S.I. units, and so $V_{\text{min}}^2$ in $V^2/\text{Hz}$. Here $F_V(kL)$ is the Cassini V-shaped antenna response, with $L$ the single wire length ($L \simeq 10\text{m}$), $C_A = \pi \varepsilon_0 L/\ln(L_D/a)$ is the antenna capacitance at low frequencies, with $a$ the wire radius ($a \simeq 1.4 \text{ cm}$), and $C_B$ is the base capacitance. Then we use an iterative method to deduce $T_c$ from (A1).

Let’s have two remarks regarding the (A1) expression:

- The V-shaped antenna and gap between the two wires on Cassini are included in the $F_V(kL)$ full calculation. If we consider the response $F|(kL)$ of a dipole such that the two wires are collinear and there is no gap between the wires, this yields: [Meyer-Vernet and Perche, 1989]

\[
F|(kL) = \left[ \frac{\text{Si}(kL) - \text{Si}(2kL)/2}{kL} - \frac{2\sin^4(kL/2)}{k^2L^2} \right] J_0^2(ka) \quad (A2)
\]

(Si denotes the sine integral function and $J_0$ the Bessel function of order 0). The full expression of $F_V$, as obtained when taking into account the angle of $120^\circ$ and $\sim 60\text{cm}$ gap between the two wires, is more complicated: for the sake of simplicity, let’s say that $F_V(kL)$ behaves as $F|(kL)$ for large $kL$ and behaves instead as $F|(kL_{\text{eff}})$ for small $kL$, where $L_{\text{eff}}$ is the effective length antenna ($\sim 9.26\text{m}$, from Gurnett et al. [2004]).

- We used here the base capacitance of the dipole antenna $C_B \simeq 55\text{pF}$. Actually Moncuquet et al. [2005] have estimated and used this value for computing the core temperature profiles at the SOI, but therein the mentioned $C_B$ was erroneous. Note our estimated value of $C_B$ agrees with the RPWS calibration correction provided since by Zaslavsky et al. [2012].
Appendix B: Dealing with shot noise and dust impact noise

We expect, when using (A1) to obtain $T_c$, that the minimum level of the spectral density is only made of electron-derived QTN. Actually the QTN analysis predicts more than a minimum, but a flat minimum level all upstream to the plasma frequency (or a constant minimum level at the gyroharmonics in case of Bernstein modes): the so-called thermal plateau (see figure B1). We observe this plateau on most of the HFR/RPWS spectra we exploited. Its presence is a very good and relevant clue that the spectral density $V^2$ upstream the plasma peak is actually dominated by the electron QTN, but it may not be the case in some of our data, and we discuss here two additional sources of noise, the shot noise which needs a rejection process and the dust impact noise, which does not affect the determination of $T_c$ in our case:

1. The shot noise provided by electrons and ions impacting the antenna (including the photoelectron emission), which is, as the QTN, unavoidable but very difficult to exploit [Moncuquet et al., 2005], in particular because it is strongly depending of the floating potential of the antenna and especially then it is depending of the full EVD, i.e., depending of the suprathermal population in case. To give an idea of the shot noise magnitude for the RPWS dipole antenna, the contribution of a Maxwellian electron population of temperature $T$, with a floating potential $\phi$, yields (in S.I. units):

$$V_f^2 = \frac{2\epsilon_0\sqrt{2\pi k_B m_e T a L}}{C_A^2} \times \left[ \frac{f_p}{f} \right]^2 \times A\left(\frac{e\phi}{k_B T}\right)$$

(B1)

Where the function $A$ is defined by $A(x) = \exp(x)$ for $x < 0$ and $A(x) = \sqrt{1 + x}$ for $x > 0$.

So, the shot noise behaves as $f^{-2}$ from B1, and it is verified in most of our spectra in the lowest part of the observed band, where it is fully dominant (see figure B1). Then
it is frequently negligible towards the plasma frequency and left unchanged the thermal plateau level (broadly speaking, it shrinks the plateau bandwidth). Our rejection method consists in using only the $f^{-2}$ behavior: we can extrapolate the shot noise from the lowest frequencies to the larger frequencies of the HFR band, so toward $f_{uh}$, where it can be compared with the QTN plateau level (green line in Fig. B1).

In summary, we consider here the shot noise as a pollution of the QTN, and we reject the spectrum (regarding the core temperature determination) when the level of the extrapolated shot noise (at the larger frequency of the plateau bandwidth) is larger than 10% of the QTN minimum level. This bring us to reject about 50% of the spectra available for the electron density determination (i.e. where $f_{uh}$ can be detected).

2. The dust impact noise, which is due to dust impacting on the whole spacecraft surface (body and antennas), each impact producing then a cloud of plasma whom charge separation and recollection produce in turn an electric field that may be detected by an electric antenna. So, contrary to the plasma noise (QTN+shot noise), this dust impact noise is not ubiquitous but reveals the presence of dust. It is worth noting however that the dipole antenna will not be sensitive to the dust impacts because the receiver measures the current balance within the two arms, so it will "see" only dissymmetrical impacts on one of the arm, while a monopole antenna will be sensitive to the voltage fluctuation between the wire and the whole spacecraft body. Because of the small surface offered by the single wire antenna compared with the large collection surface of the whole spacecraft, we conclude that the dipole is almost insensitive to the dust, while the monopole antenna will "see" any dust impacts on the spacecraft body (depending of course on the dust flux and the efficiency of the impacts to produce enough strong electric fluctuation).
is out of the scope of this paper to further describe and exploit the dust impact noise on the monopole antennas of Cassini, but let’s mention it can be done, especially for having a diagnosis on the dust itself [i.e. Meyer-Vernet et al. [2009]], but also for further investigations within the RPWS/HFR data, as for instance to discriminate the ”clean” plasma from the dusty one’s in the results presented here.

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Figure 1: Scatter plots of the equatorial electron density and core temperature close to the equatorial plane ($|z| < 0.05 \, R_S$). Panels 'a' and 'c' display color-coded profiles for each orbit from 2004 to mid 2012. The location of the icy moons of Saturn, Mimas (M), Enceladus (E), Tethys (T), Dione (D) and Rhea (R) is superimposed with vertical dotted lines. Panels 'b' and 'd' display the same set of data as in 'a' and 'c', organized in radial distance. The median radial profile obtained from the binning in 0.4 $R_S$ wide intervals for both the density and temperature is superimposed with red diamonds. The power law model of the core temperature between 2.8 and 4.8 $R_S$ ($\propto R^{2.7}$) is superimposed with a green solid line. The power law model of the density outside of 5.5 $R_S$ ($\propto R^{-1.2}$) and of the temperature outside of 4.8 $R_S$ ($\propto R^{-0.3}$) is superimposed with a blue solid line. The proton temperature model from Sittler et al. [2006] is superimposed with a light grey dashed line.
Figure 2: Correlation between the electron density and core temperature near the equatorial plane for altitudes $|z| < 0.025 \, R_S$ (Left panel) and $0.025 < |z| < 0.05 \, R_S$ (Right panel) in the 3 - 5 $R_S$ region. The median profile of the correlation is superimposed with red dots. The power law model ($n \simeq 1.2$) adjusted to the correlation for electron densities up to 80 cm$^{-3}$ is superimposed with a blue solid line. The dashed blue lines correspond to the power model plotted at 2.5 times lower and higher than its original value and underline the lower and upper envelope of the correlation.
Figure 3: Day and night radial profiles of the equatorial electron density (Top panel) and core temperature (bottom panel). Both panels display the moments averaged during the 2004-2012 time period for the dayside (0700-1700 LT; in yellow) and night side (1900-0500 LT; in blue) local time sectors (stars). The dashed lines represent the dayside and nightside electron temperature models derived by Thomsen et al. [2012] from the Cassini plasma spectrometer measurements.
Figure 4: Top panel: Normalized electron density along the orbits quasi-parallel to the equatorial plane at different altitudes (color coded, see legend -dots shows raw data, bold curves shows sliding average over $\sim 0.2 R_S$ wide window). The black line shows a power law model of equatorial density $n_e \propto L^{-4.2}$ as obtained in this paper from the equatorial density profiles (2004-2012) (and fixing $n_e=60 \text{ cm}^{-3}$ at $L=5.5$). Bottom panel: the colored curves show the plasma scale height deduced from the different orbits (sliding window average). The black heavy curve shows the sliding average profile computed over $0.5 R_S$ wide window on all orbits except rev050. The black dashed line show the power law model $\propto L^{1.53}$. 
Figure 5: Time constants of radial diffusion from *Barbosa* [1993] and thermalization of core electron with protons and heavy ions determined using the core electron density and temperature presented in this paper and the proton and heavy ion density derived by *Thomsen et al.* [2010].
Figure B1: Sample (from rev 033) of voltage power spectrum acquired on the dipole antenna, displaying the upper hybrid frequency $f_{UH}$ and the plateau $V_{\text{min}}^2$. The shot noise model ($\propto f^{-2}$) extrapolated from the three first channels of HFR (4-7 kHz) is superimposed in green.