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# Deriving the characteristics of warm electrons (100–500 eV) in the magnetosphere of Saturn with the Cassini Langmuir probe

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A B S T R A C T

Though Langmuir probes (LP) are designed to investigate cold plasma regions (e.g. ionospheres), a recent analysis revealed a strong sensitivity of the Cassini LP measurements to hundreds of eV electrons. These warm electrons impact the surface of the probe and generate a significant current of secondary electrons, that impacts both the DC level and the slope of the current–voltage curve of the LP (for negative potentials) through energetic contributions that may be modeled with a reasonable precision.

We show here how to derive information about the incident warm electrons from the analysis of these energetic contributions, in the regions where the cold plasma component is small with an average temperature in the range $\sim$[100–500] eV. First, modeling the energetic contributions (based on the incident electron flux given by a single anode of the CAPS spectrometer) allows us to provide information about the pitch angle anisotropies of the incident hundreds of eV electrons. The modeling reveals indeed sometimes a large variability of the estimated maximum secondary electron yield (which is a constant for a surface material) needed to reproduce the observations. Such dispersions give evidence for strong pitch angle anisotropies of the incident electrons, and using a functional form of the pitch angle distribution even allows us to derive the real peak angle of the distribution.

Second, rough estimates of the total electron temperature may be derived in the regions where the warm electrons are dominant and thus strongly influence the LP observations, i.e. when the average electron temperature is in the range $\sim$[100–500] eV. These regions may be identified from the LP observations through large positive values of the current–voltage slope at negative potentials. The estimated temperature may then be used to derive the electron density in the same region, with estimated densities between $\sim$0.1 and a few $particles/cm^3$ (cc). The derived densities are in better agreement with the CAPS measurements than the values derived from the proxy technique (Morooka et al., 2009) based on the floating potential of the LP. Both the electron temperature and the density estimates lie outside the classical capabilities of the LP, which are essentially $n_e > 5$ cc and $T_e < 5$ eV at Saturn. This approximate derivation technique may be used in the regions where the cold plasma component is small with an average temperature in the range $\sim$[100–500] eV, which occurs often in the $L$ range 6.4–9.4 $R_S$ when Cassini is off the equator, but may occur anywhere in the magnetosphere. This technique may be all the more interesting since the CAPS instrument was shut down, and, though it cannot replace the CAPS instrument, the technique can provide useful information about the electron moments, with probably even better estimates than CAPS in some cases (when the plasma is strongly anisotropic).

Finally, a simple modeling approach allows us to predict the impact of the energetic contributions on LP measurements in any plasma environment whose characteristics (density, temperature, etc.) are known. LP observations may thus be influenced by warm electrons in several planetary plasma regions

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in the solar system, and ambient magnetospheric electron density and temperature could be estimated in some of them (e.g. around several galilean satellites) through the use of Langmuir probes.


## 1. Introduction

Langmuir probes (Mott-Smith and Langmuir, 1926) are commonly used to investigate the cold plasma characteristics (e.g. electron temperature, density) in planetary ionospheres. The probe onboard the Cassini spacecraft – referred to as LP in the paper – is part of the Radio and Plasma Wave Science (RPWS) experiment (Gurnett et al., 2004), and provided detailed results not only about the Titan ionosphere (e.g. Wahlund et al., 2005a; Ågren et al., 2007; Garnier et al., 2009; Edberg et al., 2011; Ågren et al., 2012; Edberg et al., 2013), but also on the Saturnian plasma disk (Wahlund et al., 2005b; Morooka et al., 2009; Gustafsson and Wahlund, 2010; Holmberg et al., 2012) or dusty regions such as the Enceladus plume or the rings environment (Wahlund et al., 2009; Morooka et al., 2011; Sakai et al., 2013).

Langmuir probes' performances are limited for the derivation of the electron temperature and density: the temperature limit is due to the finite extent of the bias voltage $U_B$ applied to the probe (e.g. $\pm$ 32 V for the Cassini LP), which cannot allow to see the whole distribution if the electron temperature is too large (i.e. above $\sim$5 eV for the LP in the Saturnian magnetosphere); the electron density limit is related to the photoelectrons from the spacecraft which hide the low plasma densities (below several cc or particles per cm$^3$).

Garnier et al. (2012) – hereafter G12 – however revealed a strong sensitivity of the Cassini LP measurements to the warm electrons (the adjective “warm” will refer to energies around hundreds of eV in this paper). The analysis of the ion side current (current for negative potentials) measured by the probe showed indeed a correlation with these warm electrons, which impact the surface of the probe and generate a significant current of secondary electrons. These warm electrons correspond to the peak energy of the secondary electron emission yield (SEEY) curve for the LP surface, and are mostly observed in the dipole $L$ Shell range of $\sim$6–10 in the magnetosphere (DeJong et al., 2011).

Garnier et al. (2013) – hereafter G13 – then showed that both the DC level and the slope of the current–voltage curve of the LP (for negative potentials) are influenced by these warm electrons, through respective contributions called $I_{ener}$ and $b_{ener}$. The authors managed to model both contributions, by using several approaches (empirical or theoretical), with a reasonable precision ($\sim$40% error).

The present work follows these two previous studies and aims at deriving information about the warm electrons from the analysis of the energetic contributions $I_{ener}$ and $b_{ener}$ to the current–voltage curve. We will first briefly describe the data used in our study (Section 2) and remind the theoretical modeling of the energetic contributions by G13 (Section 3). Then, we will show that modeling the energetic contributions reveals a strong sensitivity to the pitch angle anisotropies of the incident electrons (Section 4), and that the knowledge of these contributions also allows us to derive estimations of large electron temperatures (Section 5) and low electron densities (Section 6) in specific regions of the Saturnian magnetosphere. A last section (Section 7) will show how to predict the importance of the energetic contributions for LP measurements in any plasma environment, before a conclusion ends the paper (Section 8).

## 2. Description of the data

This work is based on the simultaneous usage of data from both the Cassini LP (Section 2.1; see Gurnett et al., 2004 for a general description of the probe characteristics) and CAssini Plasma Spectrometer experiments (Section 2.2; see Young et al., 2004 for a general description of CAPS). Only a short description of these data and of the extraction of the current due to the warm electrons will be provided below, we refer the readers to G13 for a detailed description.

### 2.1. The Cassini Langmuir probe data

The LP is a Titanium Nitride (TiN) coated conductive Titanium sphere, whose bias voltage ($U_B$) is actively applied to the LP with respect to the spacecraft in order to detect the electrons or ions, depending on the sign of the potential relative to the plasma ($U = U_B + V_{float}$, with $V_{float}$ being the floating potential of the probe).

The derivation of the plasma parameters is performed through the fitting of the current–voltage ($I$–$V$) curve (Fahleson et al., 1974) using the Orbital Motion Limited (OML) theory Mott-Smith and Langmuir, 1926). We focus in this work on the ion side current ($I_-$) measured for a negative potential $U$.

G12 and G13 showed that, if we focus on regions off the equator – i.e. $Z > 2\ R_S$, with $R_S$=60,268 km the Saturn radius and ($X$, $Y$, $Z$) the Saturn centered equatorial coordinate system where $Z$ points northward along Saturn's spin axis and $X$ is in the Saturn equatorial plane positive towards the Sun – the currents induced by the presence of both charged dust and cold ions are small. The dust is indeed located near the equator, as well as the dominating water group ions that are centrifugally confined near the equator, Sittler et al., 2008). Both currents can thus be neglected compared with the photoelectron current ($I_{ph}$) due to the photoionization of the probe surface, and with the contribution due to the incident warm electrons ($I_{energet}$, which includes the incident, backscattered and induced secondary electrons).

The current for negative potentials $I_-$ actually depends linearly on the bias potential at large negative $U_B$ values (due to a current of incident ions proportional to the potential value), so that $I_-$ is parametrized by a linear equation during the data analysis process:

$$I_- = m - bU_B \tag{1}$$

where $m$ and $b$ are respectively the DC level (corrected for the spacecraft attitude) and the slope of the fitted current–voltage curve on the ion side. These two parameters are the most important parameters of the LP for negative potentials, then used to derive the ion characteristics. G13 showed that the warm electrons impact both $m$ and $b$, with contributions called respectively $I_{ener}$ and $b_{ener}$ (which thus correspond to the DC level and the slope of $I_{energet}$ the total current due to warm electrons) given by

$$I_{ener} = m + bV_{float} - I_{i_0} - I_{ph} \tag{2}$$

and

$$b_{ener} = b - b_{ions} \tag{3}$$

with $I_{i_0}$ the “random ion current” due to incident ions, and $b_{ions}$ the classic contribution of the ambient ions to the slope $b$ of the current–voltage curve. As demonstrated by G13, both contributions due to ions ($I_{i_0}$ and $b_{ions}$) are small when we focus on regions off the equator ($Z > 2\ R_S$), so that the energetic contributions $I_{ener}$