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Titan ionospheric conductivities from Cassini measurements

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ABSTRACT

We present the first results of ionospheric conductivities at Titan based on measurements during 17 Titan flybys from the Cassini spacecraft. We identify an ionospheric region ranging from 1450 ± 95 km (approximately the location of the exobase) to approximately 1000 km where electrical currents perpendicular to the magnetic field may become important. In this region the ionosphere is highly conductive with peak Pedersen conductivities of 0.002–0.05 S/m and peak Hall conductivities of 0.01–0.3 S/m depending on Solar illumination and magnetospheric conditions. Ionospheric conductivities are found to be typically higher on the sunlit side of Titan. However, Hall and Pedersen conductivities depend strongly on the magnetic field magnitude which is highly variable, both in altitude and with respect to the draping configuration of Saturn's magnetic field around Titan. Furthermore, a consistent double peak nature is found in the altitude profile of the Pedersen conductivity. A high altitude peak is found to be located between 1300 and 1400 km. A second and typically more conductive region is observed below 1000 km, where the magnetic field strength drops sharply while the electron density still remains high. This nature of the Pedersen conductivity profile may give rise to complicated ionospheric–atmospheric dynamics and may be expected also at other unmagnetized objects with a substantial atmosphere, such as e.g. Mars and Venus. Estimates of the total Pedersen conductance are found to range between 1300 and 22,000 S. The Pedersen conductance is always higher than the local Alfvén conductance but the difference varies by two orders of magnitude (from a factor 4 to 100). Thus, the conditions for reflection or absorption of Alfvén waves in Titans ionosphere are highly variable and depends strongly on the magnetic field strength.

1. Introduction

The ionospheres of Solar system bodies act as electric current layers which play an important role in the interaction of the ionosphere with the surrounding plasma environment. The flow of ionospheric currents depends strongly on the presence of a magnetic field (either internal or induced) as it leads to an anisotropic ionospheric conductivity profile. As large scale magnetospheric or Solar wind convection electric fields drive ionospheric plasma motion, a so-called dynamo region can exist in a bounded ionospheric region where atmospheric neutrals collisionally couple with the ionized components. Such a region allows for the formation of an electric circuit that couples the surrounding plasma environment with the conducting ionosphere. On planets with strong internal magnetic fields, such as e.g., Earth, Jupiter or Saturn, auroral displays in the ionosphere are associated with concentrated ionospheric currents driven by external energy sources in the magnetosphere, Solar wind, and/or atmospheric wind motion. Furthermore, anisotropically conducting ionospheres allows for electrodynamical coupling between systems of planets and moons, visualized for example as the satellite footprints in Jupiter's aurora (e.g. Clarke et al., 1996). The ability of the ionosphere to conduct an electrical current also plays an important role in the dynamics and energetics of the ionospheres as it leads to coupling of plasma convection to the neutral atmosphere and, thus, energy dissipation. It is also a controlling factor for magnetic field diffusion.

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The conductivity in the terrestrial ionosphere has been extensively studied and the theory is well developed (e.g. Boström, 1964). This paper is a first attempt to investigate the dynamo region and associated conductivity profile in the ionosphere of Titan, Saturns largest moon. It is already well-known that Titan possesses a substantial atmosphere and *in-situ* observations by the Cassini mission have confirmed the previous observations from Voyager 1 of the existence of an ionosphere at Titan (Wahlund et al., 2005; Cravens et al., 2006). Contrary to Earth, Titan does not seem to possess a strong intrinsic magnetic field. However, as Titan is embedded in the co-rotating magnetospheric plasma flow of Saturn the ionosphere is still partially magnetized as the planetary magnetic field is draped around Titan and slowly diffuses into the ionosphere of the moon (Backes et al., 2005). A similar study has already confirmed that the ionosphere of Mars is highly conductive due to the much smaller magnetic field strength compared to Earth (Dubinin et al., 2008). Based on the similarities with Mars (no strong intrinsic magnetic field, existence of an atmosphere and ionosphere) we could expect a similar electrodynamical behavior in the ionosphere of Titan. Although in this case Mars is embedded in the more dynamic interplanetary magnetic field from the Sun rather than in the magnetosphere of a large neighboring planet.

2. Conductivity model and measurements

The ability of any weakly ionized gas (e.g. Titans ionosphere) to conduct an electric current across $\vec{B}$ are given by the expressions for the Pedersen and Hall conductivities (see e.g., Boström, 1964)

$$\sigma_p = \frac{en_e}{|B|}\left[\frac{\Omega_i v_i}{(\Omega_i^2 + v_i^2)} + \frac{\Omega_e v_e}{(\Omega_e^2 + v_e^2)}\right], \tag{1}$$

$$\sigma_h = \frac{en_e}{|B|}\left[\frac{\Omega_e^2}{(\Omega_e^2 + v_e^2)} - \frac{\Omega_i^2}{(\Omega_i^2 + v_i^2)}\right], \tag{2}$$

and the conductivity along $\vec{B}$ is given by

$$\sigma_\parallel = e^2 n_e\left[\frac{1}{m_i v_i} + \frac{1}{m_e v_e}\right]. \tag{3}$$

Here e is the elementary charge, m_e the electron mass, m_i the ion mass, n_e the electron density, and $|B|$ the magnetic field magnitude. Furthermore, $\Omega_{i,e} = eB/m_{i,e}$ is the ion and electron gyrofrequency, respectively, and $v_{i,e} = \sum_n v_{in,en}$ are the ion–neutral and electron–neutral collision frequencies. The principal neutral atmospheric constituent is N_2 but CH_4, which accounts for a few percent, is also included to calculate collision frequencies for completeness. The main ionospheric ion is considered to be $HCNH^+$ (dominant at altitudes between 1000 and 1400 km, see Cravens et al., 2006), and thus $m_i = 28m_p$ where m_p is the proton mass. We assume that collisions between the charged particles (electrons and ions) and the neutral constituents of the atmosphere of Titan are predominantly of elastic nature and, thus, inelastic collisions can be neglected. The elastic ion–neutral collision frequency can be approximated by $v_{in} = 2.6 \times 10^{-9} n_n(\alpha_0/\mu_A)^{1/2}\,\mathrm{s}^{-1}$ where n_n is the neutrals number density in cm^{-3}, μ_A is the ion–neutral reduced mass in atomic units and α_0 the atomic polarizability in units of $10^{-24}\,\mathrm{cm}^{-3}$ ($\alpha_0 = 1.76$ for N_2 and $\alpha_0 = 2.59$ for CH_4) (Banks and Kockarts, 1973). The electron–neutral collision frequency for momentum transfer is given by $v_{en} = 5.4 \times 10^{-10} n_n\sqrt{T_e}\,\mathrm{s}^{-1}$($T_e$ in K) (Kelley, 1989). We have used $T_e = 0.1$ eV in this study based on observations (Wahlund et al., 2005).

This study is based on measurements from the Cassini spacecraft during the inbound and outbound legs of 17 Titan flybys[1] with a closest approach (CA) below 1200 km. They occur during a range of different illumination conditions and Saturns magnetospheric conditions. For an overview of the configuration of the flybys see Ågren et al. (2009). We use the Langmuir Probe (LP) electron density observations (24s resolution) from the Radio and Plasma Wave Science (RPWS) package on board Cassini (Gurnett et al., 2004). The neutral atmospheric densities (N_2 and CH_4 profiles are shown in Fig. 2a and b) used to calculate the collision frequencies for momentum transfer are determined from an empirical model based on Ion Neutral Mass Spectrometer (INMS) measurements (Müller-Wodarg et al., 2008) and the magnetic field magnitude (1s resolution) is acquired from the magnetometer experiment (MAG) on the Cassini spacecraft (Dougherty et al., 2004). It should be noted that comparison of the INMS densities with the equatorial HASI observations near 1000 km altitude yields INMS values about 2.4 times smaller than the HASI values. The Cassini Attitude and Articulation Control Subsystem (AACS) detects torques on the spacecraft as it enters Titan's upper atmosphere on each flyby, providing an additional independent measurement of total density. Comparison of AACS-derived densities at 1000 km and those from the INMS indicates INMS densities smaller by an average factor of 2.6 than those from the AACS, very similar to the discrepancy factor between HASI and INMS at that altitude.

3. Results

3.1. Dynamo region

In planetary ionospheres electrical currents perpendicular to the magnetic field arise in a region where the convective flow of ions is disturbed or partially disrupted by collisions with neutral atmospheric particles while the electrons are still drifting perpendicular to the magnetic and any applied electric field ($\vec{E} \times \vec{B}$ drift). This so-called dynamo region is thus restricted by the conditions $\Omega_e = v_e$ (lower boundary) and $\Omega_i = v_i$ (upper boundary). In the terrestrial ionosphere this region occurs between about 80 and 140 km in altitude. At Titan the particular altitude distribution of magnetic field and ion and neutral densities places the dynamo region at a much higher altitude than on Earth. The existence of such a dynamo region in Titan's ionosphere is identified by the shaded region in Fig. 1. This example is based on the Titan outbound leg of T30 occurring on the nightside of Titan at solar zenith angles (SZA) between 100° and 120° and around 1400 Saturn Local Time (SLT). An upper boundary of this region is found at an average altitude of 1450 km (approximately the location of the exobase) with a standard deviation of ~95 km based on the total number of 34 altitude profiles of Titan's ionosphere. An estimate of the lower boundary is unfortunately not possible for the majority of the legs as it occurs below the altitude of CA. However, it is most probably found below 1000 km and above 900 km. Thus, for an altitude range of over 450 km the effects of perpendicular electrical currents can be significant in the ionospheric–atmospheric system of Titan.

3.2. Electrical conductivities

A total number of 34 altitude profiles of the perpendicular (σ_p and σ_h) and parallel ($\sigma_\parallel$) conductivities have been determined based on the LP and MAG measurements during the 17 close Titan flybys. As, an example, Fig. 2a and b shows typical altitude profiles

[1] The dataset consists of the flybys T16–21, T23, T25–27, T30, T32, T36, T39–42 according to the Cassini project terminology.

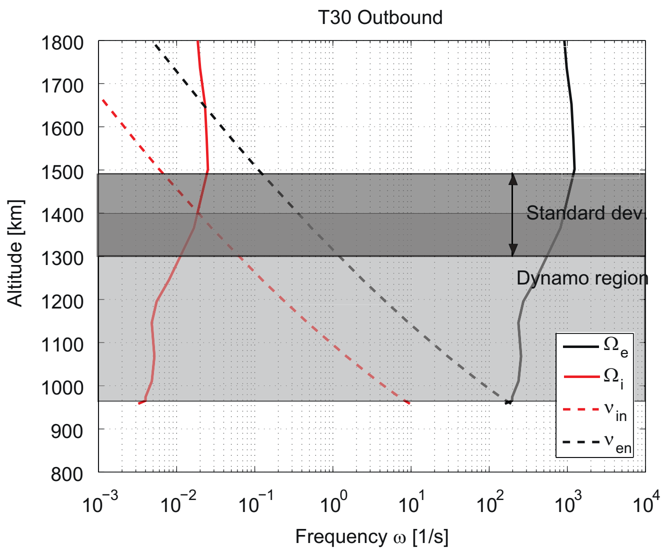

Fig. 1. The coupling region of Titan for the outbound pass of flyby T30 (shown as the shaded region). The red and black solid lines show the ion and electron gyrofrequency while the red and black dashed lines show the ion–neutral and electron–neutral collision frequencies for momentum transfer, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for the dayside Titan pass T39 (SZA 40–60°) and the nightside Titan pass T27 (SZA 110–150°), respectively. They occur during different magnetospheric conditions at ~200 SLT for T39 and ~1400 SLT for T27. The Pedersen conductivity is shown by the solid black curve while the Hall conductivity is represented by the dashed black curve. The parallel conductivity is shown by the solid blue curve. Also shown are the neutral altitude distributions (solid green for N_2 and dashed green for CH_4) and the magnetic field magnitude (red curves). The electron density altitude distributions are shown by the thick green lines and are scaled by a factor 10^5 in order to be shown on the same scale as the neutral altitude distributions. Fig. 2 shows that the ionosphere of Titan is highly conductive with a peak Pedersen conductivity of ~0.01 S/m which is about an order of magnitude higher than even the biggest values found in the terrestrial ionosphere during extreme ionospheric conditions in the auroral zone (Rosenqvist et al., 2005). No clear difference can be observed between the nightside and dayside pass as the higher electron density on the sunlit side is compensated by a stronger magnetic field strength for this particular location, resulting in similar conductivity values. A striking feature is the double peak nature of the Pedersen altitude profile for both T27 and T39.

The first peak in σ_p at the top of the dynamo layer can be considered to be related to the lower F-layer peak found in the terrestrial ionosphere. Here Eq. (1) reduces to $\sigma_p \approx en_e\Omega_i/|B|\nu_i$ ($\Omega_e \gg \nu_e$ and $\nu_i > \Omega_i$) and the Pedersen conductivity peak seems to be related to the high electron density in combination to a decrease in magnetic field strength. The primary charge carriers are the ions which are to an increasing extent collisionally coupled to the neutrals and experience a somewhat impeded $\vec{E} \times \vec{B}$ drift. At lower altitudes the ion–neutral collision frequency increases and while the electron density remains rather constant or increases somewhat the Pedersen conductivity is seen to decrease. Instead the Hall conductivity becomes dominant as the ions are now more or less completely bound to the neutrals while the electrons can still carry a Hall current as they continue their almost undisturbed $\vec{E} \times \vec{B}$ drift.

At Earth, the magnetic field is approximately constant with ionospheric altitude, but, the electron density decreases in the lower end of the dynamo region and thus both the Hall and Pedersen conductivity decrease as the electron–neutral collision frequency increases. However, in the case of Titan we observe a second peak in the Pedersen conductivity profile in the lower part of the dynamo region, which must be produced by the partially impeded $\vec{E} \times \vec{B}$ drift of the electrons. In this region Eq. (1) reduces to $\sigma_p \approx en_e\nu_e/|B|\Omega_e = m_en_e\nu_e/B^2$ ($\nu_i \gg \Omega_i$ and $\Omega_e > \nu_e$) and, thus, this second peak is due to the sharp drop in magnetic field strength observed just before CA while the electron density still remains high and fairly constant. In contrast to Earth, in the case of Titan the electron density in this region is still high enough for electrons to carry a Pedersen current as they start to collide with neutrals and move against the direction of the electric field. This sudden decrease in magnetic field magnitude has been observed previously and probably occurs in a region where a frictional force is induced by a large thermal pressure around a non-magnetized planetary object that depresses the draped external magnetic field due to force equilibrium (Neubauer et al., 2006).

Information about the conductivity altitude profile below CA can be deduced based on radio occultation estimates of the electron density performed during Titan flyby T27 (Kliore et al., 2008). As we have no magnetic field measurements available from below CA we assume that the magnetic field eventually vanishes at even lower altitudes and the ionospheric conductivity is represented by the parallel conductivity only. This is a reasonable assumption as a sharp drop in magnetic field magnitude is observed typically right before CA. The parallel conductivity on the base of the electron density profile from radio occultation measurements during T27 is shown as the blue dotted line in both Fig. 2a and b. The discrepancy between the parallel conductivity based on the electron density from the LP data versus radio occultation estimates are most probably due to the different locations of the measurements. The radio occultation measurement occurred at the limb on the sunlit side at SZA 85.7–90° and naturally both the electron density and parallel conductivity are higher than the local nightside LP estimates for T27. An estimate of the Pedersen conductance (height-integrated conductivity) can be made by connecting the parallel conductivity based on radio occultation measurements at lower altitudes with the Pedersen conductivity based on LP data at higher altitudes. This is shown by the thick shaded gray lines in Fig. 2a, b.

The resulting conductance values are given in the right corners of the panels, $\Sigma_P = 2853$ S for T39 and $\Sigma_P = 4003$ S for T27. These can be compared to the local Alfvén conductances ($\Sigma_A = 1/\mu_0 v_A$, v_A being the Alfvén velocity) taken at a reference altitude of 1600 km where $\Sigma_A = 106$ S for T39 and $\Sigma_A = 1080$ S for T27. The choice of reference altitude is not critical as Σ_A is rather constant with altitude. It can be noted that $\Sigma_P > \Sigma_A$ but only with a factor 4 for T27 compared to a factor 30 for T39 as a result of the order of magnitude higher magnetic field strength for this pass. By determining the Pedersen conductance in a similar fashion for all 34 Titan in-and outbound flyby legs one finds that Σ_P can range between 1300 and 22,000 S and the ratio between Σ_P and Σ_A varies with two orders of magnitude (a factor 4–100). This means that the conditions for reflection or absorption of Alfvén waves in Titans ionosphere is highly variable and depend strongly on the magnetic field strength.

The statistical results for the conductivity altitude profiles for all 34 legs are shown in Fig. 3a–c (Pedersen, Hall, and parallel). The different curves show the percentiles of the conductivities which is the value of the variable below which a certain percent of the observations fall. The 50th percentile (P_{50}) is the same as the median, the 25th percentile (P_{25}) is the value below which 25 percent of the observations may be found and so on. Thus, the gray shaded areas in Fig. 3a–c show the conductivity values where 50% of all observations fall and all the observations lie between

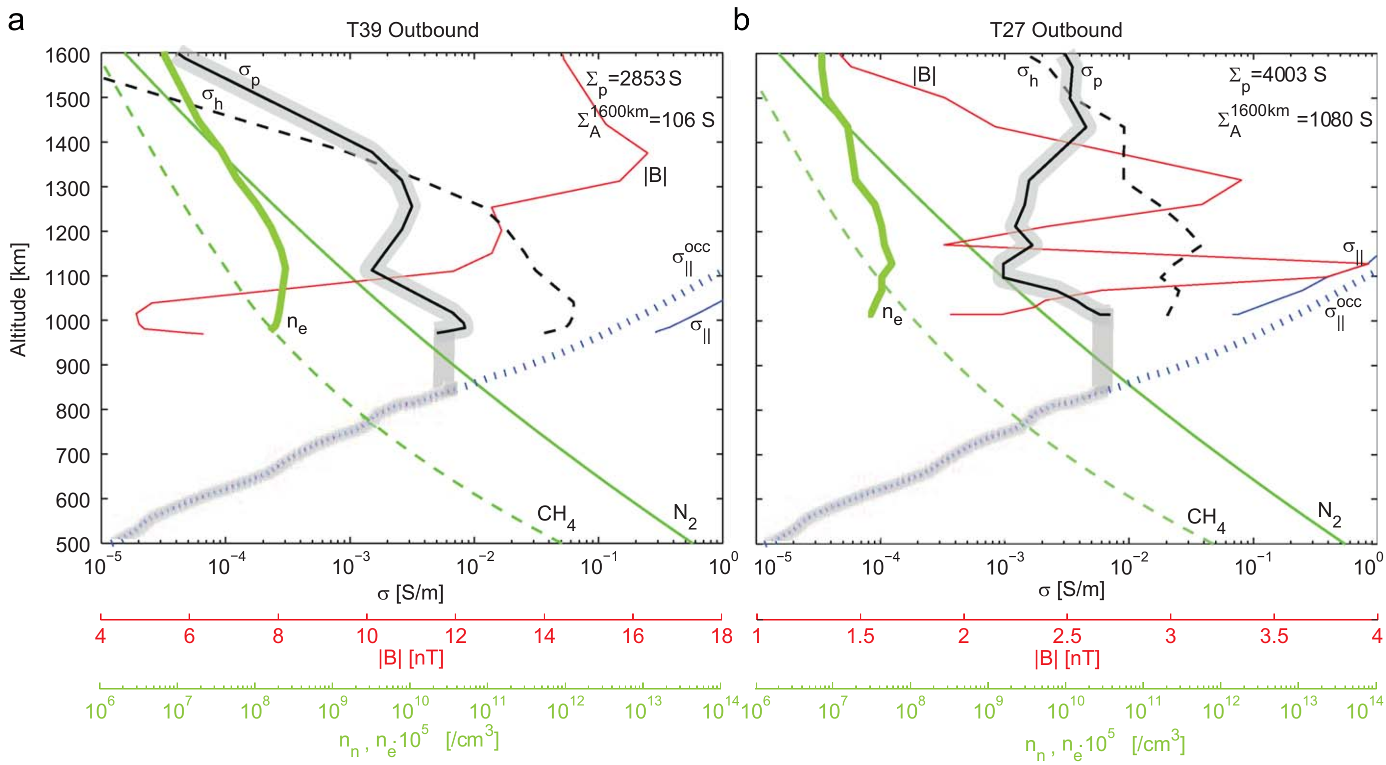

Fig. 2. Height profiles of the main neutral atmosphere components n_n (N_2 and CH_4), the electron densities (scaled by 10^5 to be shown on the same scale as n_n) the ionospheric conductivities (σ_p, σ_h, and $\sigma_\parallel$), and the magnetic field magnitude ($|B|$) for the (a) dayside Titan flyby T39 and (b) the nightside Titan flyby T27, respectively. (For interpretation of the references to colors in this figure legend, the reader is referred to the web version of this article.)

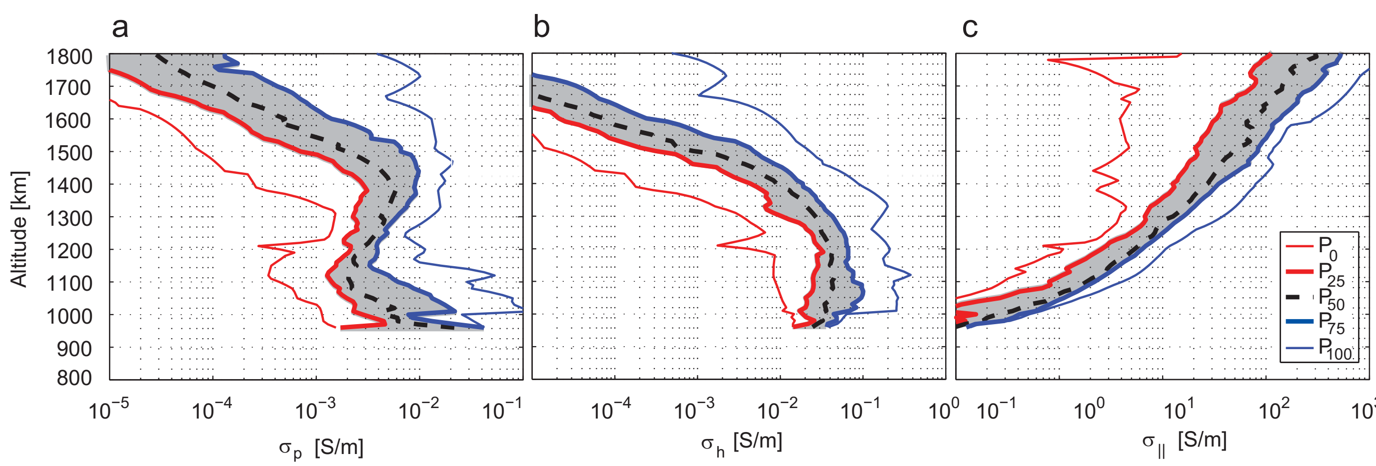

Fig. 3. Percentiles of the height profiles of the (a) Pedersen, (b) Hall , and (c) parallel conductivity observations for the entire dataset. (For interpretation of the references to colors in this figure legend, the reader is referred to the web version of this article.)

the thin red and blue lines. The double peak nature of the altitude profile for the Pedersen conductivity observed in the two cases above is clearly visible also in the statistical results (Fig. 3a). Thus, we conclude that this must be a consistent feature of the Pedersen conductivity in the ionosphere of Titan. Moreover, we can see that the first peak in Pedersen conductivity typically spans between 0.002 and 0.02 S/m while the lower second peak appears to reach even more extreme values up to 0.05 S/m. As we do not have any information below CA we can neither determine the exact altitude nor magnitude of the second peak. The peak Hall conductivity ranges between 0.01 and 0.3 S/m and the parallel conductivity approaches the Hall and Pedersen conductivities at an altitude of about 950 km.

In order to further investigate the electrodynamical nature of Titan's ionosphere we have studied the ionospheric conductivity dependency of magnetic field strength and Solar illumination conditions in terms of SZA. As Titan is embedded in the magnetosphere of Saturn the ionosphere of Titan will be subject to a wide range of magnetic conditions as it orbits around Saturn in addition to the daily variation of Solar illumination. A recent study by Ågren et al. (2009) shows that solar photons are the main ionization source of Titan's dayside only and the dayside ionosphere is 3–5 times more dense than the one on the nightside. Based on these results the dayside ionosphere should naturally be more conductive than the nightside, but we have already shown above that this is not necessarily the case due to the strong

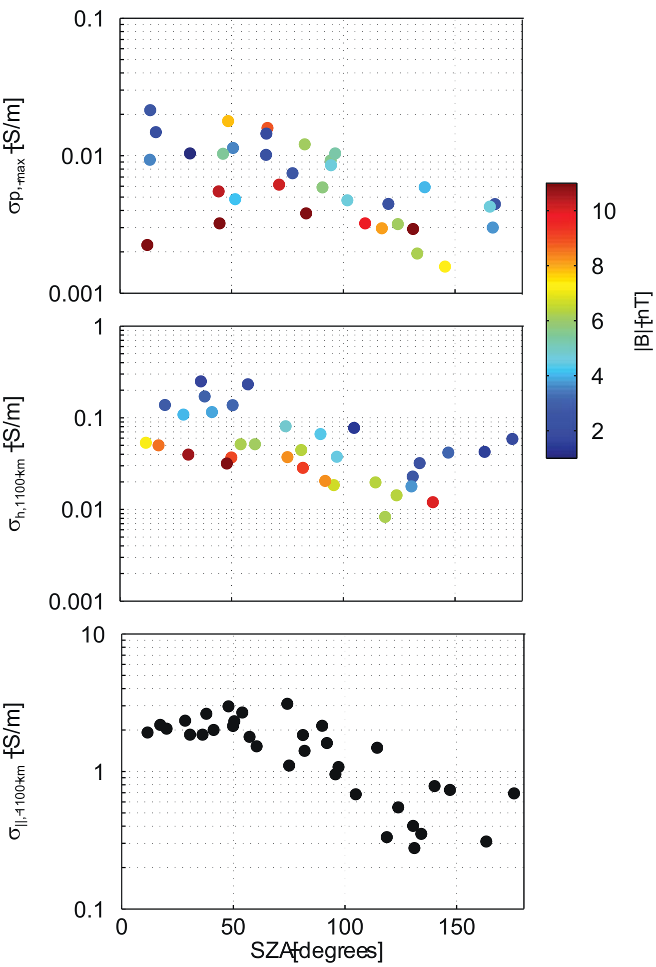

Fig. 4. SZA and magnetic field dependence (color coded) of the (a) Pedersen conductivity peak, (b) Hall conductivity, and (c) parallel conductivity at an altitude of 1100 km for the entire dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dependence of conductivities on magnetic field strength. Fig. 4a–c shows the dependence of the ionospheric conductivities on SZA and magnetic field magnitude. The datapoints in Fig. 4a (which are color-coded according to prevailing magnetic field strength) are the peak values of the Pedersen conductivity at the first peak at the top of the dynamo layer as we cannot determine the maximum of the second peak in Pedersen conductivity due to lack of data below CA. For the same reason the peak Hall conductivity is difficult to determine, but the peak is estimated to be around an altitude of 1100 km (see Fig. 3b). Thus we have chosen this reference altitude for the Hall and parallel conductivities shown in Fig. 4b and c. As the parallel conductivity is independent from magnetic field magnitude we see a clear trend of increasing parallel conductivity at 1100 km with decreasing SZA. This is fully consistent with the findings of Ågren et al. (2009) as the electron density peak was found to increase with decreasing SZA. Furthermore, similar to the findings of Ågren et al. (2009) the parallel conductivity is maximized and seems to be rather constant in the sunlit region (SZA 0–50°), decreases in the terminator region (SZA 50–100°), and reaches a minimum on the nightside of the moon (SZA 100–180°) with a rather constant magnitude. Also the Pedersen and Hall conductivities increase with decreasing SZA as shown in Fig. 4a and b. However, there is also a strong dependence on magnetic field magnitude, which is most clearly seen for the Hall conductivity, as the conductivity decreases with increasing magnetic field. Thus, Hall and Pedersen conductivities are typically larger in the sunlit ionosphere, but also depend strongly on the magnetospheric conditions of Saturn in terms of magnetic field magnitude and its draping around Titan.

4. Discussion

The observation of a consistent double peak nature of the Pedersen conductivity profile in the ionosphere of Titan raises a number of questions on the electrodynamical nature of the ionosphere of Titan. As the Pedersen conductivity is responsible for energy dissipation any electrodynamically enforced plasma motion with respect to the neutral atmosphere leads to chemical and dynamical processes in the ionosphere/atmosphere of Titan. Where $\vec{J}\cdot\vec{E}>0$, Joule heating can locally modify atmospheric dynamics and chemistry in the ionosphere/exosphere. At Earth, the ionospheric plasma energization and outflow is generally discussed in the context of field aligned current and their relation to the magnetospheric dynamo driving the current circuit (Hultqvist et al., 1999). Although Titan does not possess an intrinsic magnetic and, therefore, differs from a strongly magnetized planet like Earth, the direct exposure of the Titan top-side atmosphere to magnetospheric plasma forcing, directly transferring energy and momentum to the ionosphere, can lead to energization of ionospheric plasma and contribute to outflow and escape. The overall atmospheric chemistry could also be affected as processes that alter ion and electron temperatures and densities can lead to changed recombination rates and recombination preferences. Another interesting question is if and how the three regions of possible ionospheric currents (the identification of one Hall and two Pedersen conductivity peaks) couple to each other and to other field aligned current systems. At Earth currents typically form an electric circuit with current flowing along $\vec{B}$ from high to low altitudes where they are closed by currents flowing across $\vec{B}$. However, at Titan, the magnetic field configuration is completely different as Saturns magnetic field is draped around Titan. Thus, this allows for a completely different scenario of electric circuits.

Furthermore this also raises the question whether a similar behavior could be expected in the ionospheres of other Solar system objects that lack a strong intrinsic magnetic field, such as e.g. Mars and Venus. When Dubinin et al. (2008) investigated the Pedersen conductivity profile at Mars, they used a constant magnetic field strength. Thus, any more detailed features in the Pedersen conductivity as, e.g., found on Titan would remain unidentified as they are caused by a sharp magnetic field decrease. The decrease occurs as the lower atmosphere/ionosphere is effectively shielded from the draped magnetic field lines of Saturns magnetosphere, and similarly the Martian ionosphere should shield the planet from the draped Solar wind magnetic field. The use of a more realistic magnetic field model at Mars and an investigation of the ionosphere of Venus could shed new light on this matter.

While this paper does not attempt to answer any of these questions it is an important first step toward understanding the complicated electrodynamical nature of unmagnetized objects immersed in a magnetized plasma. The results presented here can be used to further investigate the questions raised above.

5. Conclusions

In this study, we investigated the dynamo region and conductivity profile in the deep ionosphere of Titan based on the measurements from 17 Cassini flybys. The results of this study can be summarized as follows:

- We identify the existence of an over 450 km wide ionospheric region (ranging from 1450 ± 95 km to below 1000 km) which allows for electrodynamical coupling with the surrounding magnetospheric Saturnian plasma.
- This region is shown to be highly conductive with ionospheric Hall and Pedersen conductivities exceeding those on Earth with at least an order of magnitude. Peak Pedersen conductivities are found to range between 0.002 and 0.05 S/m and peak Hall conductivities between 0.01 and 0.3 S/m depending on illumination and magnetospheric conditions.
- The ionospheric conductivities are found to be typically higher on the sunlit side of Titan, but Hall and Pedersen conductivities depend strongly on the magnetic field magnitude which is found to be highly variable.
- A previously undiscovered strong second peak in the altitude profile of the Pedersen conductivity was found in the lower region of the dynamo layer. This peak is a consequence of a sharp drop in magnetic field strength while the electron density still remains high. Thus, in the case of Titan the electrons are still numerous enough to drive a Pedersen current in this region in addition to the peak in Pedersen conductivity at the top of the dynamo layer, for which the primary charge carriers are the ions. This nature of the Pedersen conductivity profile may give rise to complicated ionospheric–atmospheric dynamics and may be expected also at other unmagnetized objects with a substantial atmosphere, such as e.g. Mars and Venus.
- Estimates of the Pedersen conductance are found to range between 1300 and 22,000 S. The Pedersen conductance is always higher than the local Alfvén conductance but the difference varies by two orders of magnitude (from a factor 4 to 100). Thus, the conditions for reflection or absorption of waves in Titan's ionosphere are highly variable and depends strongly on magnetospheric conditions.

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