Titan's interaction with Saturn's magnetosphere

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Abstract

In this brief non-systematic literature review we attempt to summarize the scientific knowledge about Titan's interaction with the Kronian magnetosphere.

Contents

1 Introduction

A magnetosphere is a region around a body in space which is partially shielded from external plasma flow by its own magnetic field exerting pressure against it (Kivelson & Bagenal, 2014). Some bodies with no intrinsic magnetic field can form a similar structure, see Section 2.1. In the cases of the planets, the plasma flow is the solar wind. Saturn has a magnetic field

Titan was discovered in 1655 by Christiaan Huygens, it is Saturn's largest moon and the second largest moon in the solar system (Lissauer & de Pater, 2019). It is an icy moon with a radius of 2575 km, a density of 1880 kg/m^3 and a surface pressure of 1.44 bar. Unlike most moons, Titan has a very dense atmosphere, being even thicker than Earth's and consisting mainly of nitrogen and a smaller amount of methane. Titan has no intrinsic magnetic field but having an orbit at 20 Saturn radii places it near the boundary of the varying Saturnian magnetic field on the sun-facing side. This combination of a dense atmosphere and the lack of an intrinsic megnetic field and its interaction with the surrounding plasma is therefore unlike that of any other moon in the solar system.

Four spacecraft have visited Saturn so far; Pioneer 11, Voyager 2, Voyager 1, and Cassini-Huygens (source!).

A major objective of the Voyager 1 project was to study Titan and its interactions with the surrounding magnetosphere (source, it is mentioned in (Hartle et al., 1982) but we will probably have some other source for describing the voyager spacecraft).

The Cassini spacecraft which was in orbit around Saturn for 13 years between 2004 and 2017 (Spilker, 2019) (it ended its mission by crashing into Saturn's atmosphere in 2017, the year after this edition of the book was published) has provided much more detailed observations of the dynamics of the Kronian magnetosphere than those from the Pioneer 10 and Voyager 1 and 2 spacecraft which only briefly passed through it (Kivelson & Bagenal, 2014).

2 Interactions between Titan and Saturn's magnetosphere

2.1 Titan's induced magnetosphere

There are two flows of charged particles across Titan; one is from the solar wind and one is from Saturn's magnetospheric plasma (Coates, 2009). The latter corotates with Saturn's rotation period of approximately $\tau_{\mathrm{plasma}} = 10.5\,\mathrm{h}$, while Titan's rotation period around Saturn is $\tau_{\mathrm{titan}} = 15.9\,\mathrm{d}$ (Lissauer & de Pater, 2019). Neglecting the eccentricity of Titan ($e \approx 0.03$) and noting that Titan orbits with a semimajor axis of $a = 1222\,\mathrm{Mm}$, this implies that the magnetospheric plasma flows at a speed of approximately

$$2\pi a \left(\frac{1}{\tau_{\mathrm{plasma}}} - \frac{1}{\tau_{\mathrm{titan}}} \right) \approx 198\,\mathrm{km\,s^{-1}}$$

relative to Titan. For comparison, the solar wind at Earth's orbit is normally around $440\,\mathrm{km\,s^{-1}}$, although it can vary greatly (Gosling, 2014). Since Titan orbits in the same direction as saturn spins around its axis, the ram side of this plasma flux is "behind" Titan rather than in front. The difference in direction between the flow of particles from the sun and from the magnetospheric plasma changes during the local day on Titan, as illustrated in Figure 1. When Titan is inside Saturn's magnetosphere it is partially shielded from the solar wind, meaning that the corotating plasma is the dominating flow (Coates, 2009). This is the situation that has been most studied since most observations by spacecraft have been in such conditions.

The magnetospheres of most planets as well as Jupiter's moon Ganymede arise from an intrinsic magnetic field generated via a process called magnetohydrodynamic dynamo (Kivelson & Bagenal, 2014). Titan has no such magnetic field, but it possesses a conducting ionosphere. When the corotating plasma flows across Titan, currents are induced in its ionosphere that create forces that oppose the oncoming flow. This results in an induced magnetosphere around the body, with a magnetotail "in front". The magnetic field around Titan changes rapidly only very close to its surface. In contrast to the planetary magnetospheres which are subjected to the supersonic solar wind, the induced magnetosphere of Titan has no bow shock since the oncoming plasma flow is slower than both the Alfvén speed and the sound speed of the plasma.

Voyager 1 carried a plasma science instrument which was used to make around 20 measurements of energy spectra for electrons and ions in the wake of Titan during a flyby in 1980. In a paper by Hartle et al. (1982), the
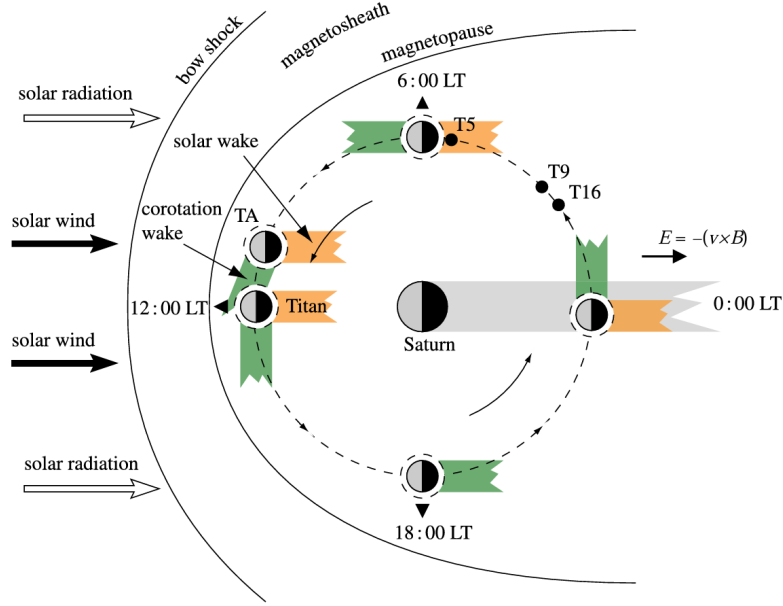
Figure 1: An illustration of Titan's two plasma flow wakes in its orbit around Saturn. Taken from Coates (2009).

data from these measurements were analyzed and interpreted to give insights into the structure of Titan's induced magnetosphere and especially its magnetotail. Figure 2 illustrates the trajectory of the spacecraft during the flyby, projected onto Titan's orbital plane with the X-axis pointing in the corotation direction and and Y-axis pointing towards Saturn. Some results from the electron measurements are presented in figures 3a and 3b. The first figure shows the velocity distributions across the wake of Titan, and a clear "bite-out" can be seen where there are almost no electrons with speeds higher than about $16\,\mathrm{Mm\,s^{-1}}$ (730 eV).

The Voyager 1 spacecraft also had a magnetometer which recorded measurements of the magnetic field along its trajectory during the same flyby in 1980. Ness et al. (1982)

A 2009 study by Rymer et al. (2009) classifies Titan's plasm environment into four different categories based on electron thermal data from 54 encounters on titan by Cassini as follows.

1. The **plasmasheet** contains high energy electrons whose peak enegy is on the oder of 100s eV. The electron density is also high in this region with fluxes at $10^6 cm^{-2}s^{-1}sr^{-1}$. This was the most common environment, with 19 encounters.

2. The **lobe-like** region also has high energy electrons, with peak energies similar to or higher than that of the plasmas sheet. The electron density is however smaller with fluxes an order of magnitude less. 8
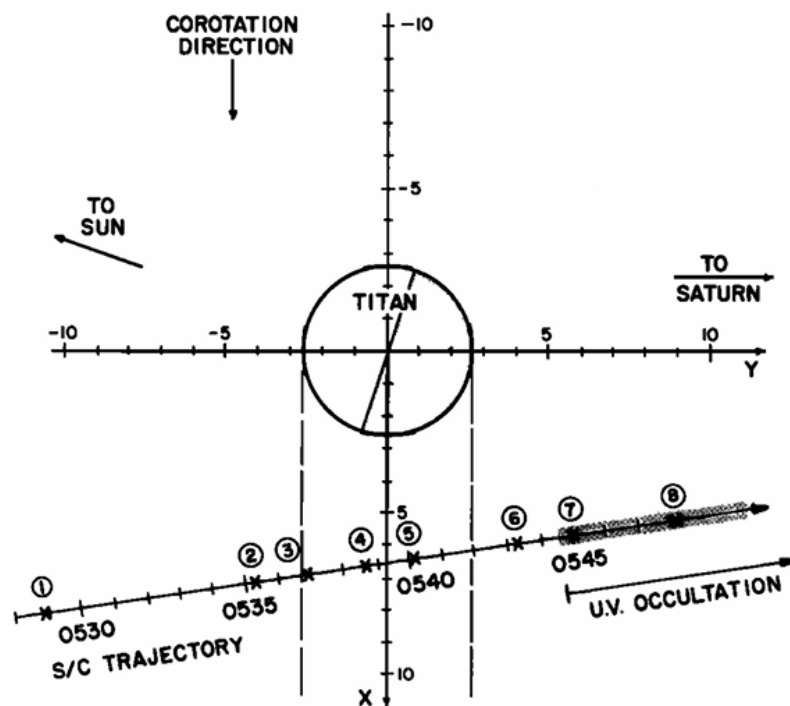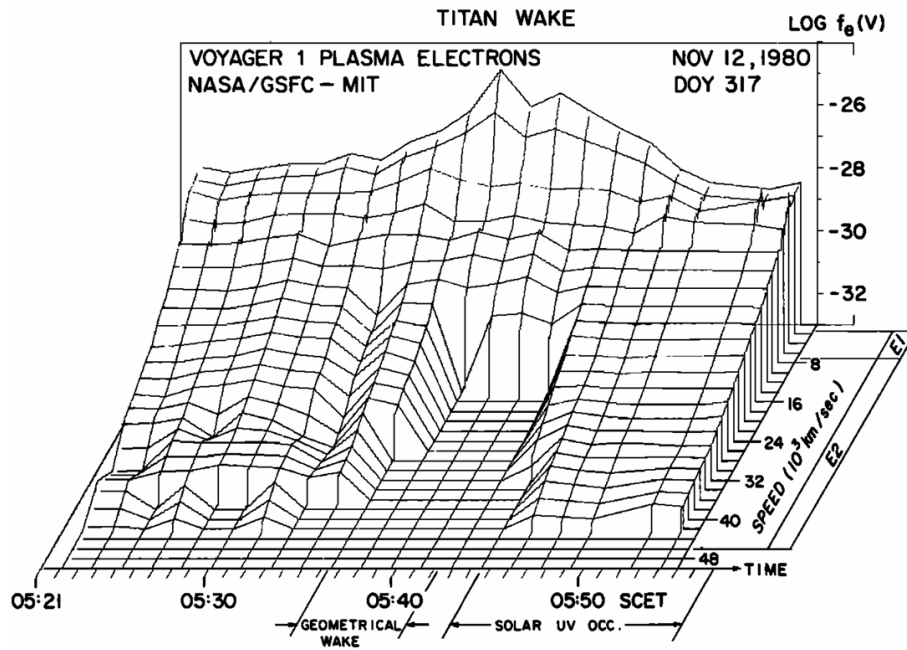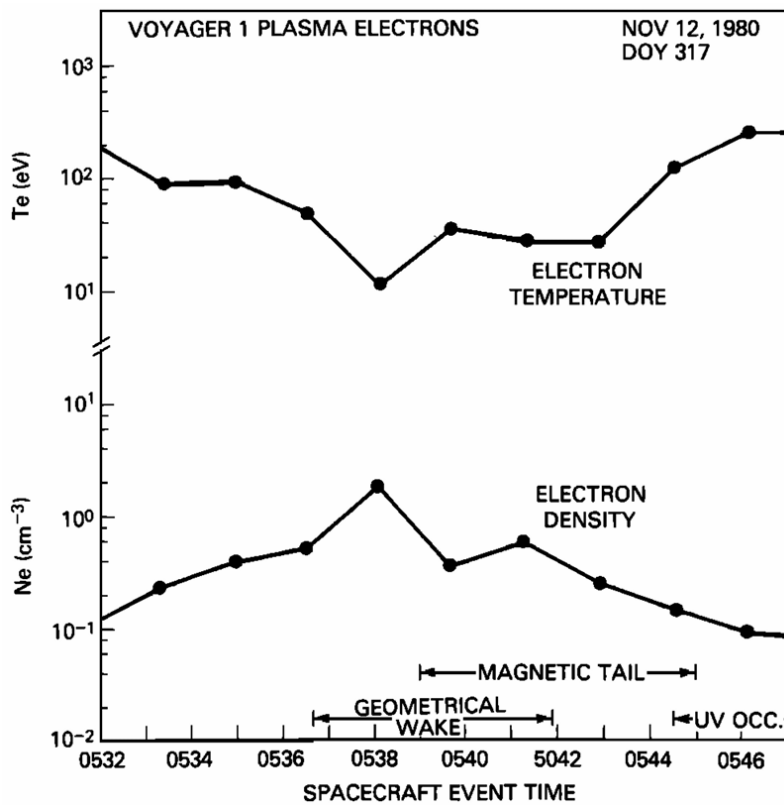
Figure 2: An illustration of the flyby of Titan by Voyager 1 on the 12th of November 1980. The trajectory is projected onto Titan's orbital plane. The units of the coordinates are Mm and the numbers along the trajectory are the spacecraft-local time points. Adapted from Hartle et al. (1982).

(a) Electron speed spectra.

(b) Electron temperature and density measurements.

Figure 3: Plots from Hartle et al. (1982) of electron enery spectra, temperatures, and number densities in Titan's wake recorded by the plasma science experiment on Voyager 1.

encounters with this environment was made.

3. The **magnetosheath** is encountered outside of the magnetopause, and thus consists of plasma from the solar wind. In this region electrons are of lower energy, but higher density than the previous two classes. 2 encounters with this environment was made.

4. The **Bi-modal** region is highly variable, containing two seperate electron populations, hence bi-modal. One is similar in energy to the plasma sheet or Lobe-like category. The other population is less energetic but more dense and consists of so called local pick-up population that comes from a neutral cloud, where produced electrons are quickly picked up by the co-rotation with Saturn gaining energy on the order of tenths of eV. The electron energy seen is higher though, which is thought to be explained by these electrons originating from photoionization of larger ions where the energy released is on the order of 10eV. These heavy ions are believed to be water groups, which originate in the inner magnetosphere of Saturn, from the moon Enceladus and migrates outwards to Titan. 5 encounters of this environment was made.

A paper by Smith and Rymer (2014) further examines more encounters by cassini, establishing that 45% of encounters are plasma sheath, 38% are lobe-like, 6% magnetosheath. The plasma envionment along Titans obit, when the planet is not curently present is also examined, here 55% of encountes are plasma sheath, 24% are lobe like and 12% are magnetosheath. This suggest that the precence of Titan lowers the probablity of expeiencing the magnetosheath, meaning that Titan extends the magnetopause of Saturn outwards. The authors cannot conclude this however, due to possible sampling bias that needs to be analysed more rigouresly. An earlier paper by Wei et al. (2009) draws a similar conclution. This study looks at the specific time intervall of 0900 - 1500 Saturn local time (SLT) and examines the plasma environment in 26 cases with and 37 without Titan present. The percentage of time in the magnetosheath was 3.37% near Titan 10.37% away from Titan, which is statistically significant. The implication of this is that the compressation of the plasma is hindered by Titans' presence (Wei et al., 2009).
Smith and Rymer (2014) also finds that the bi-modal environment is more prevelant in the vicinity of Titan compared to the orbit of Titan without the moon precent. This suggests that ionization is greater with Titan present, as the origin of the low energy population of the bi-modal environment is thought to be pick up ions.

An additional classification of the plasma environment, dubbed dense plasma region is also recognized by Smith and Rymer (2014). In this environment

the electron energies can be compared to the low energy plasma of the Bi-modal environment, but the higher energy electrons seen in the Bi-modal environment are not precent. Additionally, the environment is more long lived than the Bi-modal low energy electrons. This environment was seen during dusk, no theory of its origin could be found.

2.2 Energetic particle interactions

2.2.1 Mass loading

2.2.2 Charge-exchange collisions

(Dandouras et al., 2009) Titan not having an intrinsic magnetic field makes it directly susceptible to the oncoming plasma flow, these interactions were captured using the magnetosphere imaging instrument (MIMI) and the ion and neutral mass spectrometer (INMS) onboard the Cassini spacecraft. The instruments were able to detect that energetic ions from Saturn's magnetosphere undergo charge-change collisions with slow neutral atoms in Titan's upper atmosphere, producing energetic neutral atoms (ENAs). The reaction describing a charge-exchange collision is $X^+ + Y \longrightarrow X_{ENA} + Y^+$, where X^+ is the energetic ion, Y is the colliding cold neutral atom, X_{ENA} is the resulting energetic neutral atom, and Y^+ is the ionized particle. Charge-exchange collisions is one of the reasons for Titan's exosphere being in thermal inequilibrium, with some other reasons being sputtering and photodissociation. Data from Cassini flybys indicated that the highest amount of particle collisions occured in the lower atmosphere causing most of the produced ENAs to be absorbed, resulting in a darker region in the ENA image of Titan's exosphere as can be seen in figure 4.
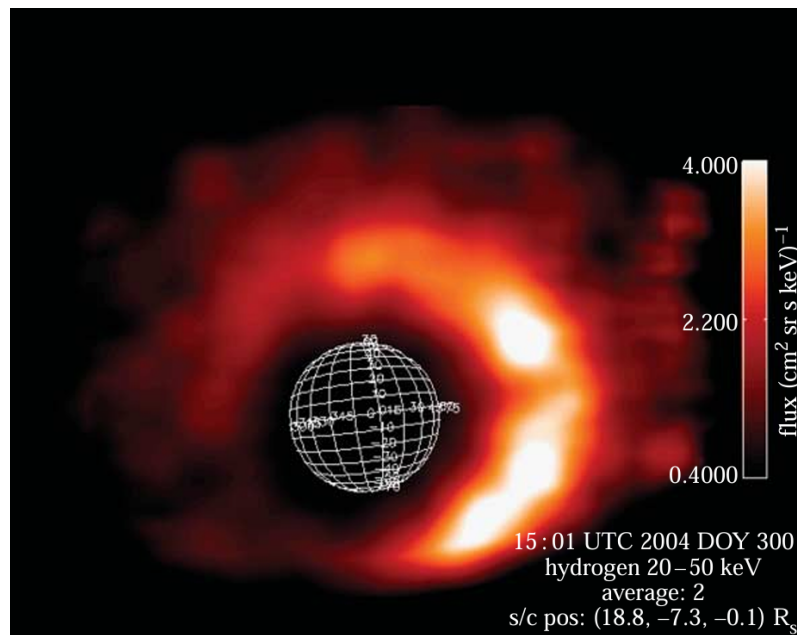
3 Conclusions

Figure 4: Image of ENAs in Titan's exosphere taken by the MIMI during a Cassini flyby. Taken from Dandouras et al. (2009).

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