Titan's interaction with Saturn's magnetosphere

Alexander Ek, John Persson, Björn Sundin

October 8, 2024

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). The magnetic field is "draped" around the body, and meets the oncoming flow at a *magnetopause* where the pressures from the external plasma and the magnetic field are equal. On the wake side, a *magnetotail* forms as the magnetic field is stretched out. Some bodies with no intrinsic magnetic field can also form a similar structure, as is the case for Venus and Saturn's biggest moon Titan (see Section 2.1). In the cases of the planets, the oncoming plasma flow is primarily the solar wind.

Saturn has a conducting supercritical fluid hydrogen interior which through a process called magnetohydrodynamic (MHD) dynamo generates a magnetic moment about 600 times greater than Earth's. Its magnetic field rotates at approximately the same rate as Saturn itself, with some variation along its orbit around the Sun. Saturn's magnetosphere contains neutral and charged particles originating from various sources among which are the interstellar and solar winds, Saturn's inner icy moons (via sputtering and the geyser on Enceladus), Titan's and Saturn's atmospheres and ionospheres, and Saturn's rings (Blanc et al., 2005). Due to friction in Saturn's atmosphere and ionosphere, the magnetospheric plasma rotates with the same period as Saturn spins about its axis. It is mostly concentrated around the equator because of the centrifugal forces in Saturn's rotating reference frame.

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 (launched 1973, flyby 1979), Voyagers 1 and 2 (launched 1977, flybys 1980 and 1981 respectively), and Cassini-Huygens (launched 1997, flyby 2004) ("Appendix", 2014). A major objective of the Voyager 1 project was to study Titan and its interactions with the surrounding magnetosphere (Hartle et al., 1982). The Cassini spacecraft which was in orbit around Saturn until it ended its mission by crashing into Saturn's atmosphere in 2017 (Spilker, 2019) 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 $\tau_{\text{plasma}} = 10.5\,\text{h}$, while Titan's rotation period around Saturn is $\tau_{\text{titan}} = 15.9\,\text{d}$ (Lissauer & de Pater, 2019). Neglecting the eccentricity of Titan ($e \approx 0.03$) and noting that Titan orbits with a semimajor axis of $a = 1222\,\text{Mm}$, this implies that the magnetospheric plasma flows at a speed of approximately

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

relative to Titan. For comparison, the solar wind at Earth's orbit is normally around $440\,\text{km}\,\text{s}^{-1}$, 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 MHD 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

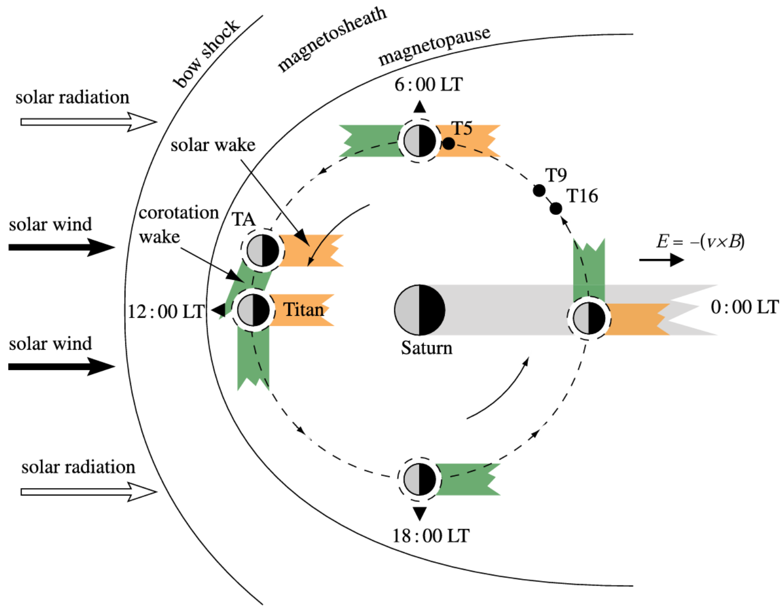


Figure 1: An illustration of Titan's two plasma flow wakes in its orbit around Saturn. Taken from Coates (2009).

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 data from these measurements were analyzed and interpreted to give insights into the structure of Titan's 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. The flyby took place at 13:30 local solar time (as defined in Figure 1) (Ness et al., 1982). 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 second figure also shows that this wake region is more dense than the surroundings.

The Voyager 1 spacecraft also had a magnetometer which recorded measurements of the magnetic field along its trajectory during the same flyby in 1980. These were analyzed in Ness et al. (1982). The magnetotail was found to be perturbed by about 20° from the coration direction towards Saturn, likely caused by the difference in irradiation from the Sun between the night and day sides of Titan's ionosphere. Figure 4 illustrates possible mag-

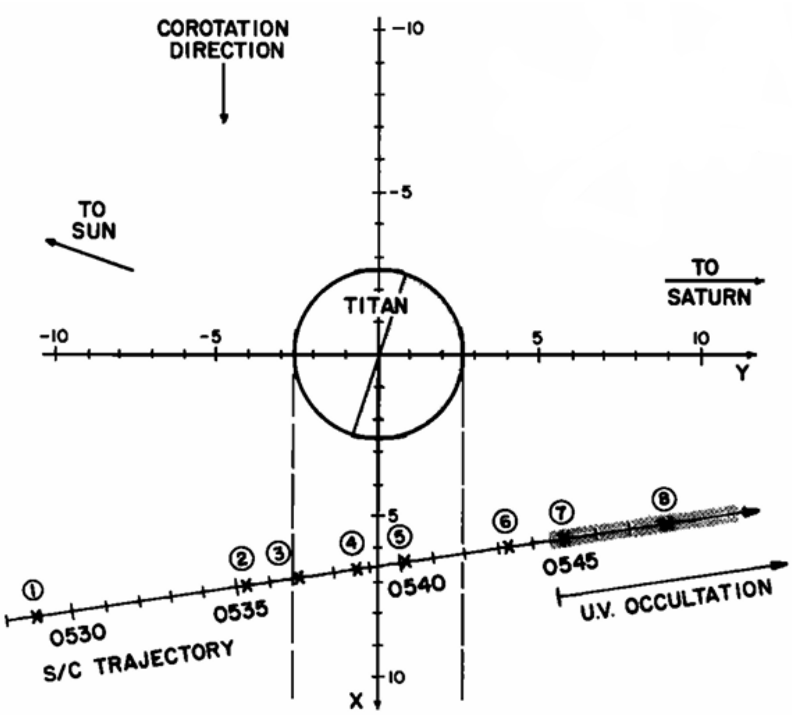
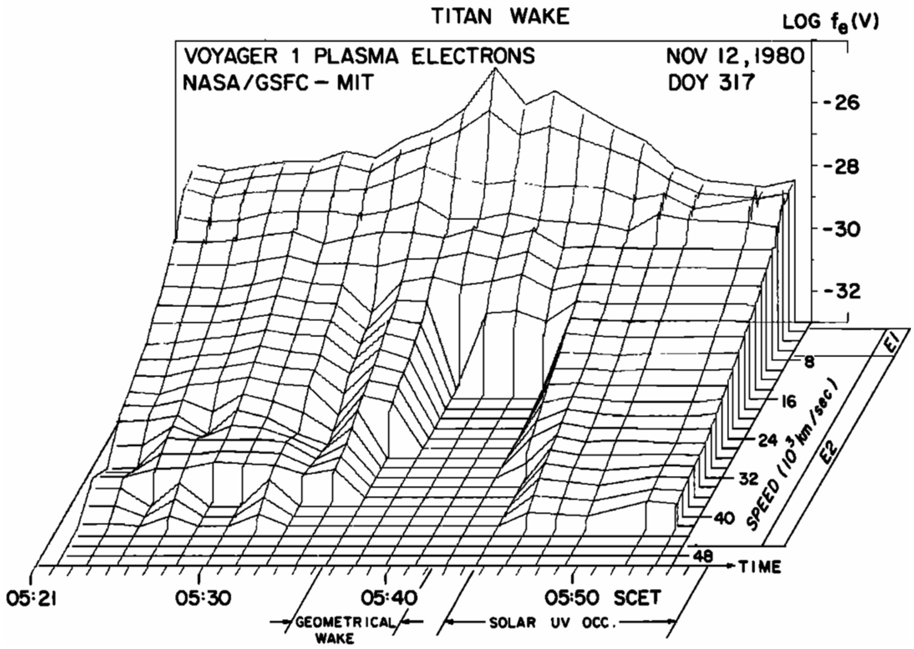
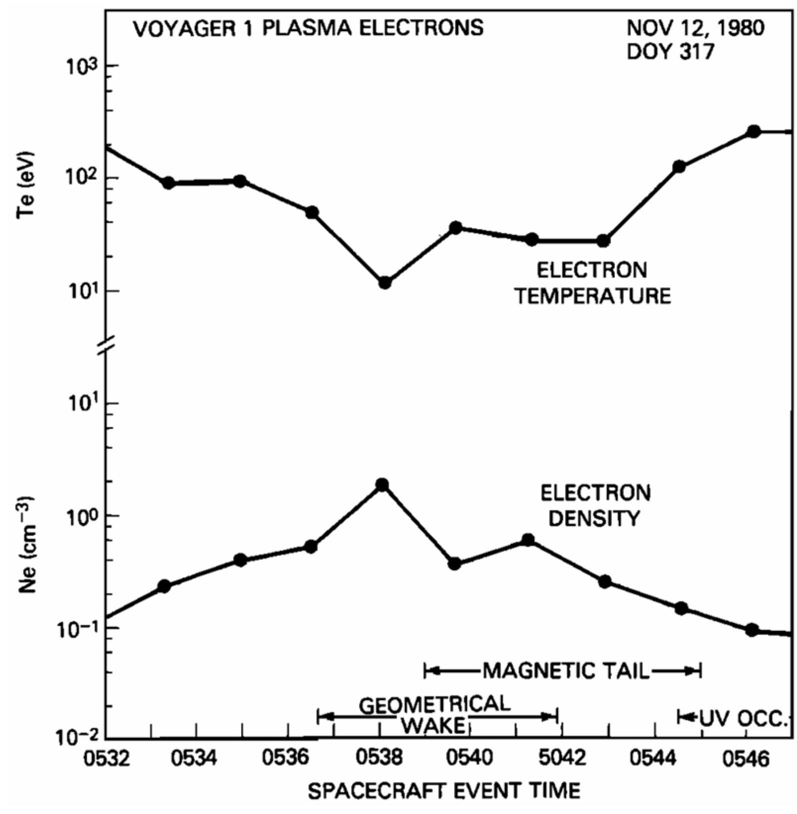


Figure 2: An illustration of the flyby of Titan by Voyager 1 on the 12th of November 1980. The trajectory is projected onto Titan's orbital plane. The units of the coordinates are Mm and the numbers along the trajectory are the spacecraft-local time points. Adapted from Hartle et al. (1982).



(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.

netic field lines based on this data.

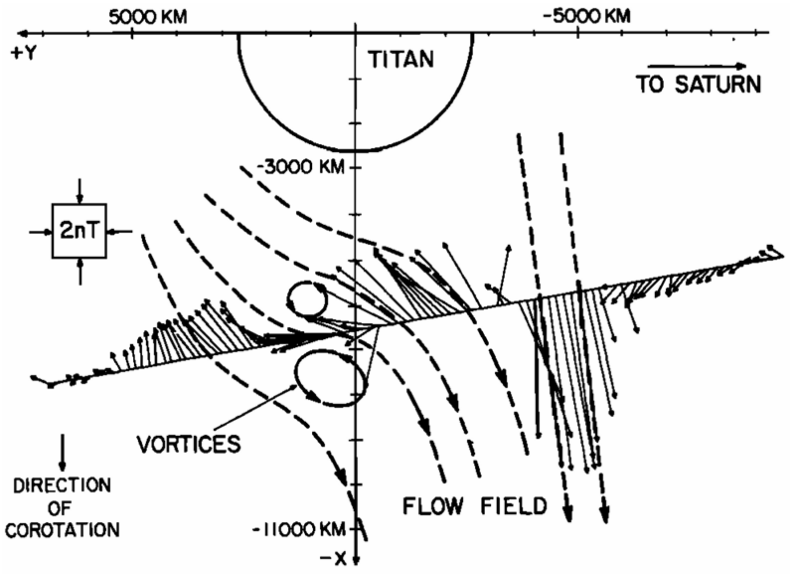


Figure 4: Magnetic field lines in the wake of Titan as inferred by Ness et al. (1982) based on magnetometer data from Voyager 1.

During cassinis T9 flyby, the magnetotail was analysed at mid-ranges, 5-6 titan radii downstrteam in terms of magnetometer data and electron enegy and count by Bertucci et al. (2007).

In a paper by Kim et al. (2024), the data from the T122-T126 Cassini flybys of Titan was used to analyze its magnetotail structure. The magnetotail was found to display variations over time and space. In two of the flybys (T123 and T124) an Alfvén wing-like structure was observed in the magnetic field around Titan. Alvenic wing-like structures are created when Titan is exposed to sub-magnetosonic flow from Saturn's magnetospheric plasma and is a direct consequence of Titan not having an internal magnetosphere. The wing-like structures connects the field lines of Saturn's magnetosphere with Titan's ionosphere. A bipoloar magnetotail with an embedded neutral current sheet in the magnetotail was also observed in the T122 flyby, as has been observed earlier by the Voyager 1 flybys (Ness et al., 1982).

A 2009 study by Rymer et al. (2009) classifies Titan's plasma 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 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, containg 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 present. 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 present. 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

Titan not having an intrinsic magnetic field (Dandouras et al., 2009) 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-exchange 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 deviating from thermal equilibrium, 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 5.

3 Conclusions

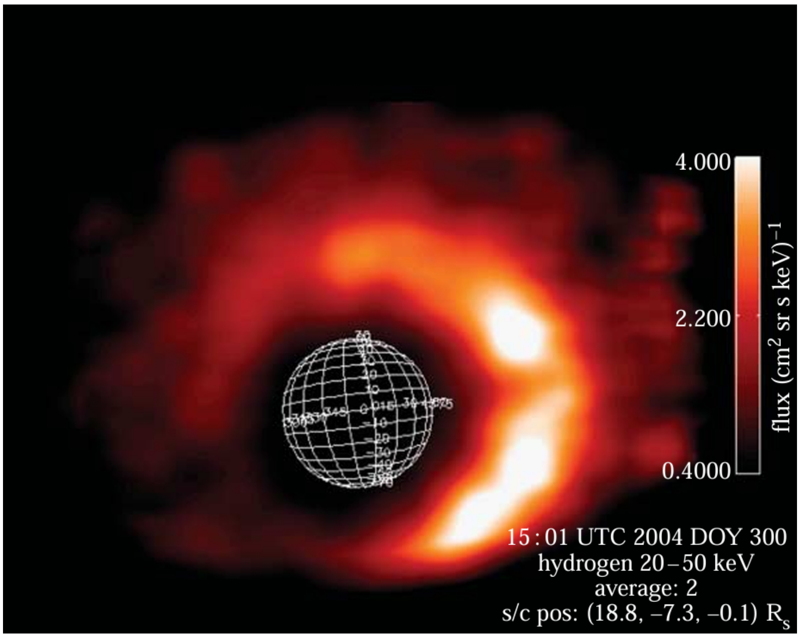


Figure 5: Image of ENAs in Titan's exosphere taken by the MIMI during a Cassini flyby. Taken from Dandouras et al. (2009).

References

Appendix. (2014). In T. Spohn, D. Breuer, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (third edition)* (Third Edition, pp. 1235–1259). Elsevier. https://doi.org/10.1016/B978-0-12-415845-0.15001-7

Bertucci, C., Neubauer, F. M., Szego, K., Wahlund, J. E., Coates, A. J., Dougherty, M. K., Young, D. T., & Kurth, W. S. (2007). Structure of titan's mid-range magnetic tail : Cassini magnetometer observations during the t9 flyby. *Geophysical Research Letters*, *34*(24), L24S02–. https://doi.org/10.1029/2007GL030865

Blanc, M., Kallenbach, R., & Erkaev, N. V. (2005). Solar system magnetospheres. *Space Science Reviews*, *116*, 227–298. https://doi.org/10.1007/s11214-005-1958-y

Coates, A. J. (2009). Interaction of titan's ionosphere with saturn's magnetosphere. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *367*(1889), 773–788. https://doi.org/10.1098/rsta.2008.0248

Dandouras, I., Garnier, P., Mitchell, D. G., Roelof, E. C., Brandt, P. C., Krupp, N., & Krimigis, S. M. (2009). Titan's exosphere and its interaction with saturn's magnetosphere. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *367*(1889), 743–752. https://doi.org/10.1098/rsta.2008.0249

Gosling, J. (2014). Chapter 12 - the solar wind. In T. Spohn, D. Breuer, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (third edition)* (Third

Edition, pp. 261–279). Elsevier. https://doi.org/10.1016/B978-0-12-415845-0.00012-8

Hartle, R. E., Sittler Jr., E. C., Ogilvie, K. W., Scudder, J. D., Lazarus, A. J., & Atreya, S. K. (1982). Titan's ion exosphere observed from voyager 1. *Journal of Geophysical Research: Space Physics*, *87*(A3), 1383–1394. https://doi.org/10.1029/JA087iA03p01383

Kim, K., Edberg, N. J. T., Wahlund, J.-E., & Vigren, E. (2024). Alfvén wing-like structures in titan's magnetotail during t122-t126 flybys. *Journal of Geophysical Research: Space Physics*, *129*(6), e2023JA032265. https://doi.org/10.1029/2023JA032265

Kivelson, M. G., & Bagenal, F. (2014). Chapter 7 - planetary magnetospheres. In T. Spohn, D. Breuer, & T. V. Johnson (Eds.), *Encyclopedia of the solar system (third edition)* (Third Edition, pp. 137–157). Elsevier. https://doi.org/10.1016/B978-0-12-415845-0.00007-4

Lissauer, J. J., & de Pater, I. (2019). *Fundamental planetary science: Physics, chemistry and habitability*. Cambridge University Press.

Ness, N. F., Acuna, M. H., Behannon, K. W., & Neubauer, F. M. (1982). The induced magnetosphere of titan. *Journal of Geophysical Research: Space Physics*, *87*(A3), 1369–1381. https://doi.org/10.1029/JA087iA03p01369

Rymer, A. M., Smith, H. T., Wellbrock, A., Coates, A. J., & Young, D. T. (2009). Discrete classification and electron energy spectra of titan's varied magnetospheric environment. *Geophysical Research Letters*, *36*(15). https://doi.org/10.1029/2009GL039427

Smith, H. T., & Rymer, A. M. (2014). An empirical model for the plasma environment along titan's orbit based on cassini plasma observations. *Journal of Geophysical Research: Space Physics*, *119*(7), 5674–5684. https://doi.org/10.1002/2014JA019872

Spilker, L. (2019). Cassini-huygens' exploration of the saturn system: 13 years of discovery. *Science*, *364*(6445), 1046–1051. https://doi.org/10.1126/science.aat3760

Wei, H. Y., Russell, C. T., Wellbrock, A., Dougherty, M. K., & Coates, A. J. (2009). Plasma environment at titan's orbit with titan present and absent. *Geophysical Research Letters*, *36*(23). https://doi.org/10.1029/2009GL041048