

Titan Interaction with Saturn's Magnetosphere: Mass Loading and Ionopause Location

By

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We investigate the details of Titan's interaction with Saturn's magnetosphere, which includes formation of an ionopause and its location and mass loading via ion pickup. We present some new interpretations of the Voyager 1 encounter results, not previously done by Hartle and coworkers [1]. Using arguments based on theory and observation we show that in the outer pickup region, ion pickup of H^+ and H_2^+ dominates, with some mass loading effects. Only when the flow has reached the exospheric population dominated by heavy neutral species such as methane and molecular nitrogen does the flow experience major mass loading and slowing down. We do find that large ion gyroradii of the pickup ions could be important to the interaction, but not significant enough that during the Voyager 1 encounter with Titan for the plasma instrument to detect energetic beams of heavy ions in the energy spectra. The plasma instrument did measure pickup ion distributions, where the dominant ion was consistent with H_2^+ , but could also be CH_4^+ . Our calculations also include ejection of relatively energetic heavy neutrals such as atomic nitrogen from Titan's upper atmosphere due to electron, ion and photon impact. We also show finite gyroradius effects from the interaction of the ambient plasma with Titan's atmosphere, which results in an asymmetric removal of ambient plasma from Titan's ion exospheric region. The Voyager plasma data shows the removal of the keV ambient population first during the approach and then the less energetic ambient component being removed. During the outbound phase the less energetic ambient component reappeared with the keV ambient component reappearing further away. This feature is consistent with finite gyroradius effects with the energetic component being a heavy ion component like N^+ and the light ion component being H^+ and confirms the original analysis by Hartle and coworkers [1] that the ambient plasma was composed of a light and heavy ion component. We comment on the position of the ionopause, its characteristics and the corresponding access of charged particles to Titan's upper atmosphere similar to that done for Triton [2]. The position of the ionopause plays a critical role with regard to the strength of the source term for Titan's nitrogen torus [3]. The addition of CH_4 in our exosphere calculations indicate, that Titan could also be an important source of carbon to Saturn's magnetosphere. In the future we plan to use a 2D-hybrid code with an exosphere model, to model Titan's interaction with Saturn's magnetosphere. These results, can then be used to make predictions for the Cassini flybys of Titan.

1.0 INTRODUCTION

During the Voyager 1 encounter with Saturn it had a close encounter with the moon Titan on November 12, 1980 where it detected a complex interaction with Saturn's outer magnetosphere as originally reported in [4] and [5]. These initial results were followed by the more comprehensive analysis by [1], [6] and [7]. The encounter results showed that the sonic Mach number was less than 1, no shock was detected and the magnetometer did not detect an internal magnetic field for Titan. In many respects, because of Titan's extended atmosphere and exosphere the encounter could be considered similar to that of a comet. In Table 1 we summarize some of the plasma and magnetic field properties of the encounter, as originally presented in [1] and [7]. This Table shows that the upstream plasma was a high beta plasma with $\beta > 10$. Most of the plasma pressure resides in the heavy ion component that had keV temperatures. Hartle and coworkers [1], showed that the ambient ion population had gyroradii $r_g > 5000$ km for the heavy ion component, which was assumed to be N^+ . These gyroradii are larger than the physical dimensions of Titan, which made finite gyroradius effects an essential feature of the interaction. Therefore, the use of MHD codes to model the interaction may not apply, although such models were developed later on to model the interaction [8]. Later, [9] did develop a 3D hybrid calculation of the interaction. This model only included a single ion component and used an ad hoc description of the pickup ion process. The analysis by [1] demonstrated that the inbound pass was very complex and that pickup ions were observed. This result was supported by the enhanced levels of wave emissions observed by the Plasma Wave System (PWS) instrument during the inbound approach and reported by [10] and [11]. In the analysis by Hartle and coworkers [1] they modeled the pickup ions by using a ring distribution which then had to be convoluted with the instruments response of the Plasma Science (PLS) instrument (see [12] for a description of the instrument). In order to simulate the pickup process they used an exosphere model composed of H and N_2 . The exospheric model they used was originally developed by [13,14,15]. For this application they assumed spherical symmetry, but in general it has a 3D capability and can include upper atmospheric winds at the exobase as a boundary condition. In their initial paper they concluded that protons were the dominant species for the pickup ions observed. This conclusion was partially based on the fact that ion beams were not observed by the plasma instrument.

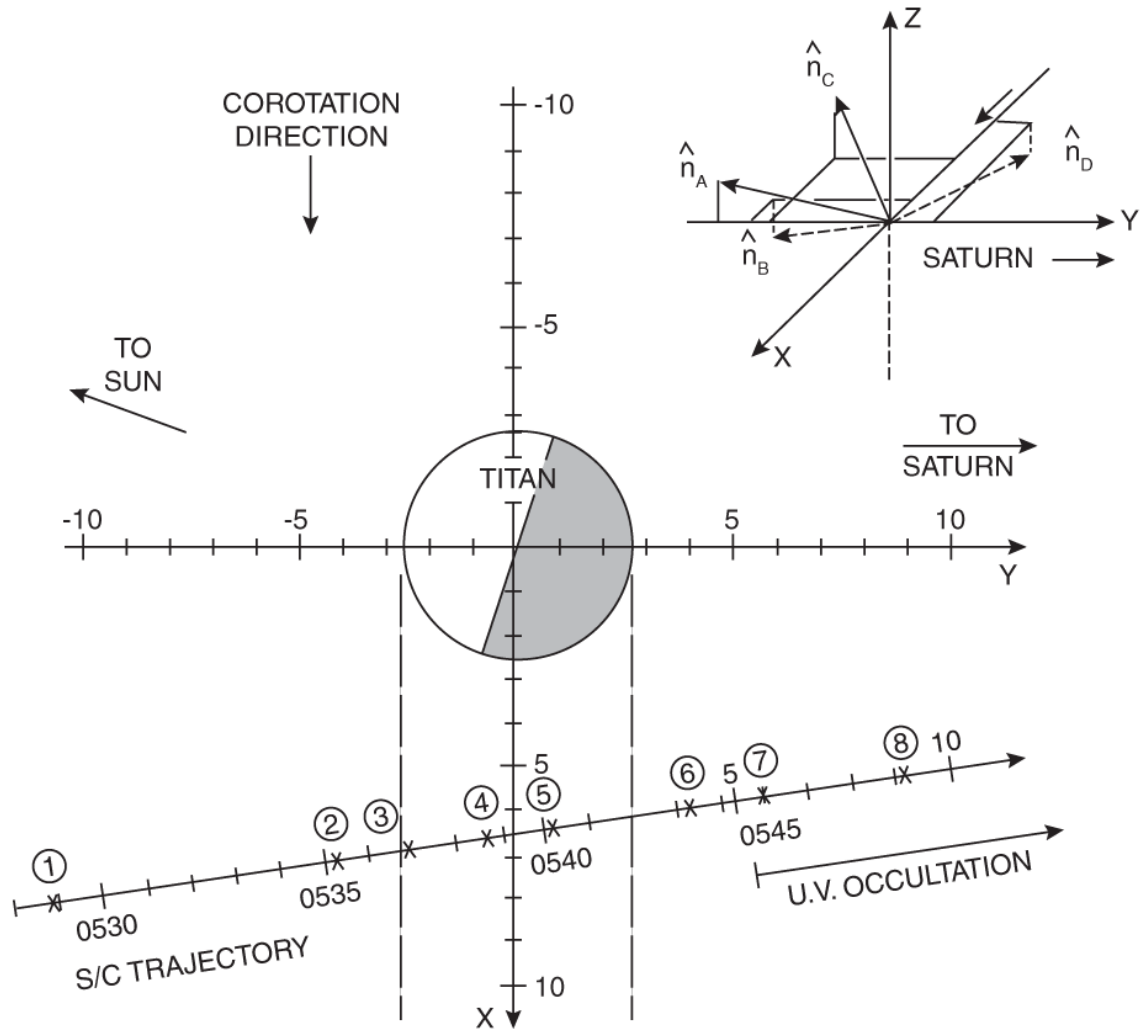
Table 1. Plasma Upstream Properties: Voyager 1 Titan Flyby¹

Parameter	Value
Magnetic Field B	5 nT
Flow Speed V	80-150 km/s
Proton Density n_p	0.1 cm^{-3}
Nitrogen Ion Density n_{N^+}	0.2 cm^{-3}
Electron Temperature T_e	200 eV
Proton Temperature T_p	210 eV
N^+ Temperature T_{N^+}	2.9 keV
Total Plasma Pressure p	$10^{-9} \text{ dyne/cm}^2$
Plasma β	11

Alfven Speed V_A	64 km/s
Sound Speed V_S	210 km/s
Alfven Mach Number $M_A = V/V_A$	1.9
Sonic Mach Number $M_S = V/V_S$	0.57

Parameters derived from Hartle et al. (1982) and Neubauer et al. (1984)

For this paper we will revisit the original analysis performed by Hartle and coworkers [1] and provide new insights about the nature of the interaction. In addition to H and N_2 , we have added H_2 , CH_4 and exothermic nitrogen atoms, N^* , to our exospheric model. We then use this model to compute mass loading of the plasma by pickup ions, which are



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Figure 1.

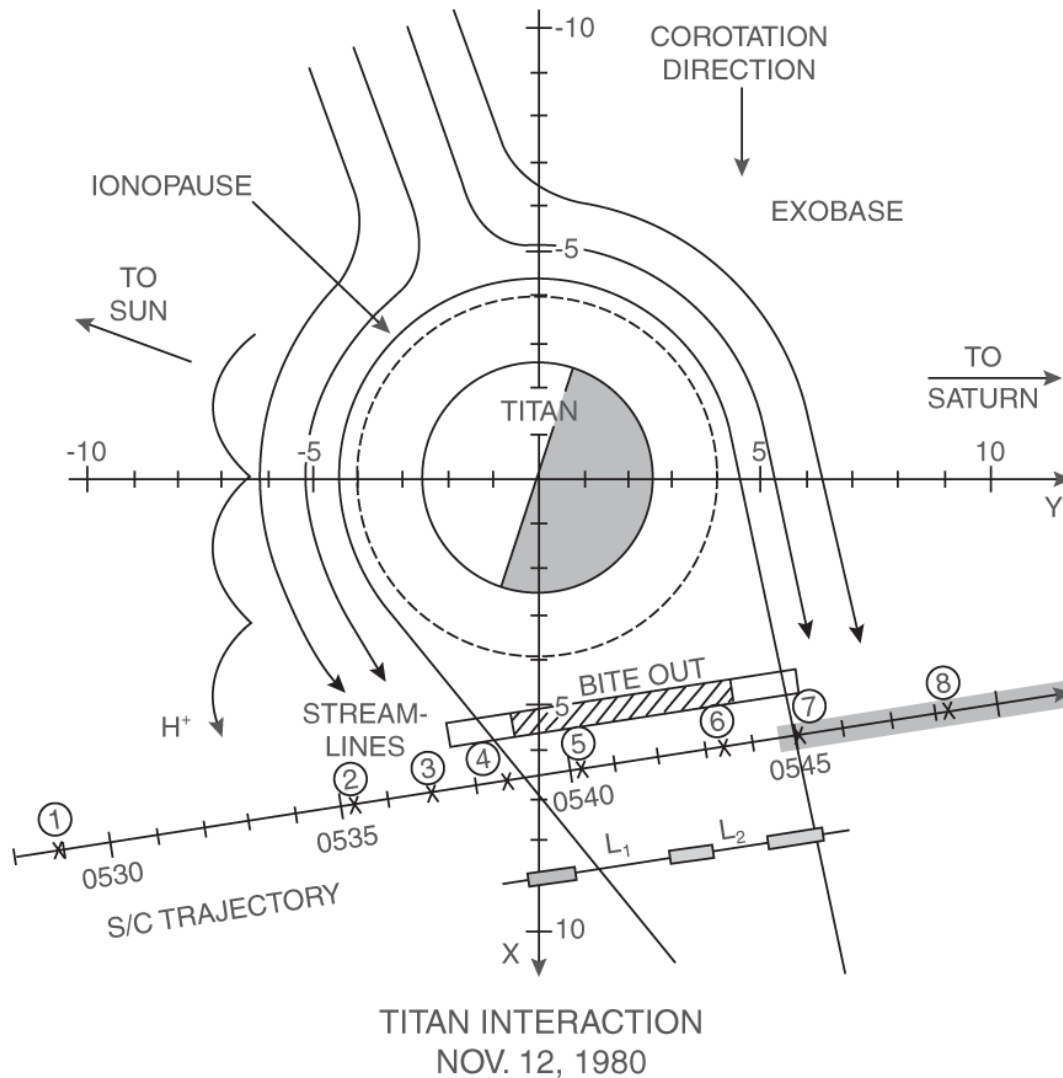


Figure 2.

formed by ionization of the neutral exosphere. The important ionization processes are photoionization, electron impact ionization and charge-exchange. We will look into the importance of local time variations of the exospheric temperature on our model calculations and corresponding effects on the Titan interaction. These results will set the stage for the future development of hybrid calculations of the interaction similar to that done by [9], which did not include an exosphere in their model calculations. The hybrid calculations will include elastic/inelastic collisions, charge-exchange reactions and photoionization.

2.0 VOYAGER 1 ENCOUNTER WITH TITAN REVISITED

2.1 Encounter Geometry

In Figure 1 we show the Voyager 1 flyby geometry, along with the view axis of the A, B, C and D cups of the plasma instrument during the encounter period. The wake in the corotational direction of Saturn's rotating magnetosphere is also indicated. Along the trajectory are indicated the location, numbers 1 to 8, where the PLS ion spectra were analyzed for purposes of characterizing Titan's interaction with Saturn's magnetosphere. The sensor alignment is such that the D cup is pointing directly into the corotation direction, the C cup has partial alignment along the corotation direction, while the A and B cups look at right angles to the corotation direction. The ambient plasma will be coming from the corotation direction and was observed to be moving ~ 120 km/s as reported by [1]. The pickup ions will show maximum flux along the corotation direction and give the largest signal in the D cup. It is important to note that the sunlit side of Titan faces toward the inbound approach of the spacecraft trajectory. Titan was near local noon relative to Saturn and thus near the magnetopause boundary.

2.2 Inferred Model of Interaction

In Figure 2 we show the inferred properties of Titan's interaction with Saturn's magnetosphere as originally envisioned by Hartle and coworkers [1]. The figure shows the estimated location of the ionopause, $R_{\text{ion}} \sim 4400$ km, and location of the exobase, $R_{\text{exo}} \sim 4000$ km. The ionopause altitude is therefore ~ 1800 km. The Cassini spacecraft, for its planned 40 plus Titan encounters, will come as close as 1000 km or less of Titan's surface. As discussed in [3], the height of the ionopause will play a critical role with regard to the importance of Titan's nitrogen torus within Saturn's magnetosphere. When one lowers the height of the ionopause the magnetospheric plasma will have greater access to Titan's upper atmosphere with a corresponding increase in the number of ejected nitrogen atoms into the torus region. The figure also shows a deflection of the wake by about 20° from the corotational direction, which was interpreted by [1] to be caused by an inward deflection of the magnetopause due to an increase in solar wind pressure and Titan's close proximity to the magnetopause. The figure shows the presence of pickup hydrogen ions, which were observed during the spacecraft's inbound approach of Titan's flyby. This is expected, because on the side facing away from Saturn the pickup ions will gyrate away from Titan's atmosphere, while on the other side the pickup ions will immediately ram into Titan's atmosphere and be lost. Finally, the figure shows a bite-out region where the fluxes of magnetosphere $E > 500$ eV electrons were removed by interactions with Titan's upper atmosphere. At lower energies, within the bite-out region, we have secondary electrons from ionization of the atmosphere (i.e., photoelectrons) and possibly the remnants of magnetospheric electrons that have been degraded by inelastic collisions with Titan's upper atmosphere.

2.3 Analysis of Plasma Data: New Results

In Figure 3 we show, as done in [1], the eight PLS ion spectra analyzed for their study of the Titan interaction. Spectra 1 and 8 were measured when the spacecraft was far from

the interaction region and showed the presence of very hot ambient magnetospheric plasma. Hartle and coworkers [1] determined that the plasma was composed of a light and heavy ion component, which they inferred to be H^+ and N^+ . This plasma was moving with speeds ~ 80 - 150 km/s with mean value ~ 120 km/s. The temperature of the heavy component was ~ 3 - 4 keV and the plasma $\beta \gg 1$. In Table 2, we show the estimated ion gyro-radii for the ambient plasma, spectrum 1, and possible pickup ion components for

Table 2. Ion Drift Speeds and Gyro-Radii at Titan

Spectrum #	Parameter	H^+	N^+	N_2^+
1	Thermal Speed	200 km/s	200 km/s	140.0 km/s
1	Gyro-Radius	400 km	5600 km	7840 km
2	Drift Speed	175 km/s	47 km/s	33 km/s
2	Gyro-Radius	350 km	1316 km	1848 km
3	Drift Speed	85 km/s	23 km/s	16 km/s
3	Gyro-Radius	170 km	636 km	896 km
4	Drift Speed	60 km/s	10 km/s	5 km/s
4	Gyro-Radius	120 km	280 km	280 km

spectra 2, 3 and 4. As can be seen the gyro-radii for ambient protons is ~ 400 km, while that for N^+ is ~ 5600 km, which is greater than the diameter of Titan. By looking at Figures 1, 2 and 3 one can see in spectrum 2 evidence of an attenuation of the ambient nitrogen ions (i.e., nitrogen ions reside toward keV energies), and the likely presence of

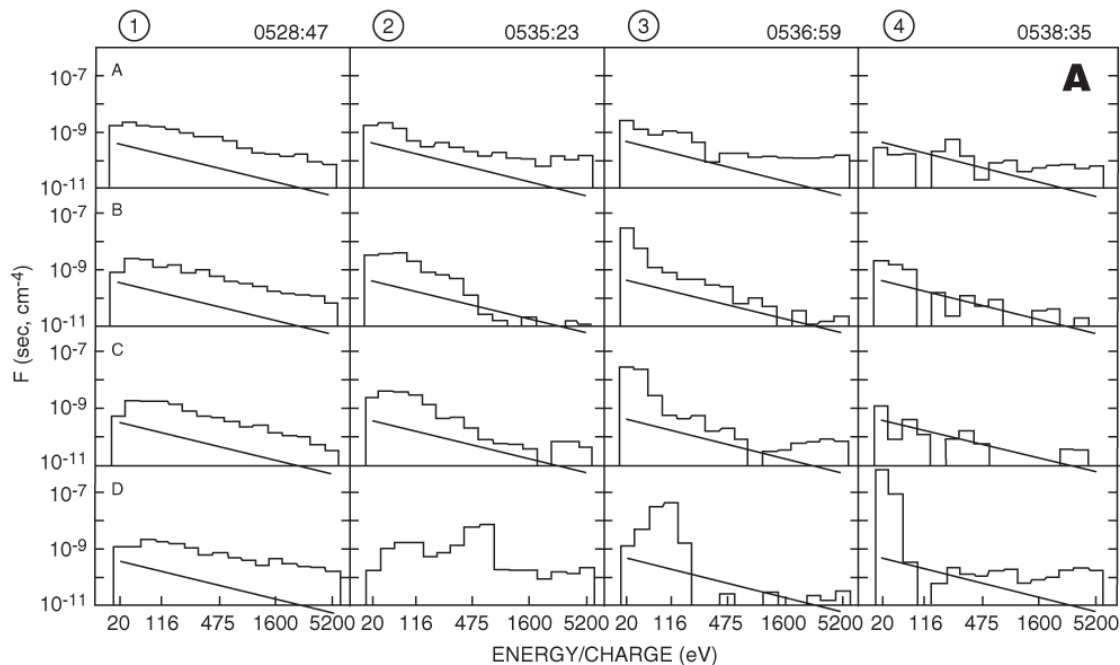


Figure 3A.

pickup ions in the D cup at energies extending up to 500-1000 eV (At the time of spectrum 2 the spacecraft is ~ 5500 km from the center of the deflected wake). But, the

ambient protons are essentially unaffected. In spectrum 3 the ambient nitrogen ions are essentially removed and the ambient protons are also showing attenuation toward higher energies. The dominant feature for this spectrum is the presence of a pickup ion component with energy below a few hundred eV. The magnetometer data indicates that spectrum 4 is just outside the wake region, while spectra 5 and 6 are in the wake region. Then in spectrum 7, when the spacecraft exits the wake, the ambient protons first appear and then in spectrum 8 both ambient protons and nitrogen ions have completely recovered. Overall inspection of these figures indicates a preference for the ambient nitrogen ions to be removed during the inbound pass relative to that seen on the outbound pass. This result is consistent with the presence of finite gyroradius effects during the interaction between Titan and the magnetospheric plasma. In spectrum 2, during the inbound pass, the gyroradii of the ambient nitrogen ions are \sim the distance Voyager 1 is from the wake region. If they are to be detected by either cups C or D, their guiding centers must be on the Titan side with respect to the spacecraft. Therefore, these ions will have a high probability of gyrating into Titan's atmosphere and be lost from the plasma flow. In the case of ambient protons, their gyroradii are only \sim 400 km, and will not encounter Titan's atmosphere, thus showing little attenuation. Because spectrum 3 is within 1000-2000 km of the wake, and the ambient ion guiding centers are on the Titan side of the spacecraft, ambient nitrogen has a higher likelihood of encountering Titan's upper atmosphere and disappear from the plasma flow, as observed. The same can be said for spectrum 7 during the outbound pass. The absence of ambient nitrogen in spectrum 7 is consistent with their large gyroradii and closeness of the spacecraft to the wake. While the ambient protons with their smaller gyroradii show nearly full recovery. In order for the ions to be observed by cups C and D, their guiding centers must be further away from Titan with respect to the spacecraft to increase their probability of not encountering Titan's upper atmosphere. By spectrum 8, the spacecraft is \sim 3000 km from the wake. Since the guiding centers of these ions are on the side away from Titan, they do not encounter Titan's atmosphere and as observed have no attenuation. Referring to Figure 1, one can infer that ions entering cups A and B, have their guiding centers further away from Titan during the inbound pass, relative to that required for cups C and D. Therefore, especially for cup A, which looks furthest from the corotation direction than the other three sensors, that ambient nitrogen ions are present in the A cup as expected for spectrum 2. Cup D in Figure 3 does show some signal up to 5 keV, but this could be due to a heavy pickup ion component forming further upstream before mass loading has taken effect (i.e., $r_g \sim 7300$ km). In the case of the A and B cups during the outbound pass, for

ions to be seen in spectrum 7, their guiding centers must be shifted toward Titan with

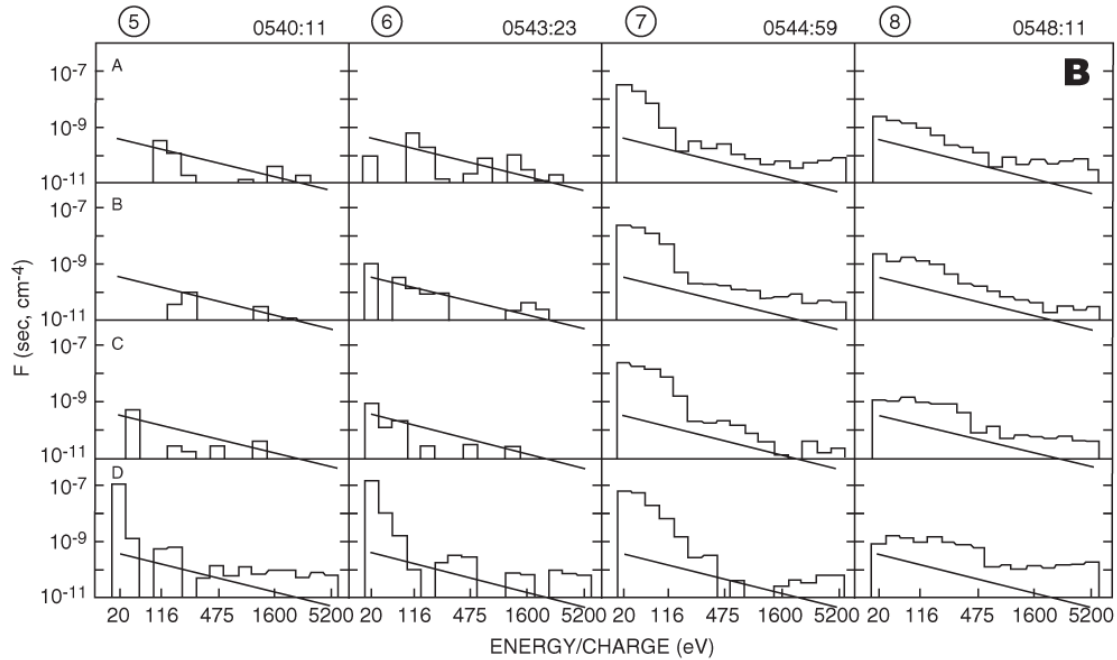


Figure 3B.

respect to the ion trajectories sensed by cups C and D. Therefore, the guiding centers of ambient protons must be ~ 400 km from the upper atmosphere of Titan (i.e., exobase). The location of the inferred boundary of the wake, as shown in Figure 2, is consistent with this interpretation. Therefore, it should be clear from the above discussions, that finite gyroradius effects do play a major role in the physics of Titan's interaction with Saturn's magnetosphere and that the ambient plasma is composed of a light (i.e., H^+) ion component and a heavy (i.e., N^+) ion component.

Returning to spectrum 2, the location of the high energy edge of the pickup ion peak will be equivalent to twice the flow speed of the plasma if they are described by a ring distribution (see [16]). In Table 2 we indicate our estimated drift speeds of the plasma for an assumed composition of the pickup ions. If protons, the inferred drift speed of 175 km/s exceeds our upper estimate of 150 km/s for the flow speed of the ambient plasma. In the case of N^+ (equivalent to CH_4^+) the drift speed is ~ 50 km/s, which is below our lower range of 80 km/s for the flow speed of the ambient plasma. But, if possible, it would be consistent with some mass loading of the plasma by the pickup ions. We will come to this point later in the paper. If the ion is N_2^+ , the drift speed is ~ 33 km/s. Note that the gyroradii of the pickup ions are $350 \text{ km} < r_g < 1800 \text{ km}$, considerably less than the gyroradii of ambient nitrogen ions $r_g \sim 5600 \text{ km}$. For spectrum 3, where the pickup ions are confined below a few hundred eV, the estimated drift speeds are ~ 85 km/s, 23 km/s and 16 km/s for H^+ , N^+ (CH_4^+) and N_2^+ , respectively. At this point, considerable mass loading of the plasma has occurred. We also see a further decrease of the gyroradii of the pickup ions for which $170 \text{ km} < r_g < 900 \text{ km}$. Finally, in spectrum 4, the spectral peak is confined below the low energy cut-off of the PLS instrument, 10 eV, and the inferred flow speeds are 60 km/s, 10 km/s and 5 km/s for H^+ , N^+ (CH_4^+) and N_2^+ ,

respectively. Here, the plasma flow is very close to the wake boundary and severe mass loading of the plasma has occurred and, as concluded by Hartle and coworkers [1], is probably composed of N_2^+ ions. At this point, the flow is becoming more fluid like, where the gyroradii are now $120 \text{ km} < r_g < 280 \text{ km}$. These issues will be addressed when we perform mass loading calculations of the plasma later in the paper. In conclusion, we can say, further from the wake, finite gyro-radii effects are dominant, while near the ionopause boundary, the flow becomes more fluid like. Therefore, future models must take these issues into account. The transition region from large gyroradii (i.e., hybrid code) to small gyroradii (i.e., MHD code) is expected to be very complex and difficult to model accurately. The numerous close encounters of the Cassini spacecraft with Titan will allow us to constrain future model development of the interaction over a wide range of spacecraft encounters and Titan interaction geometries, which could include Titan's interactions within Saturn's magnetosheath or possibly the solar wind.

3.0 TITAN'S EXOSPHERE

3.1 General Exosphere Properties

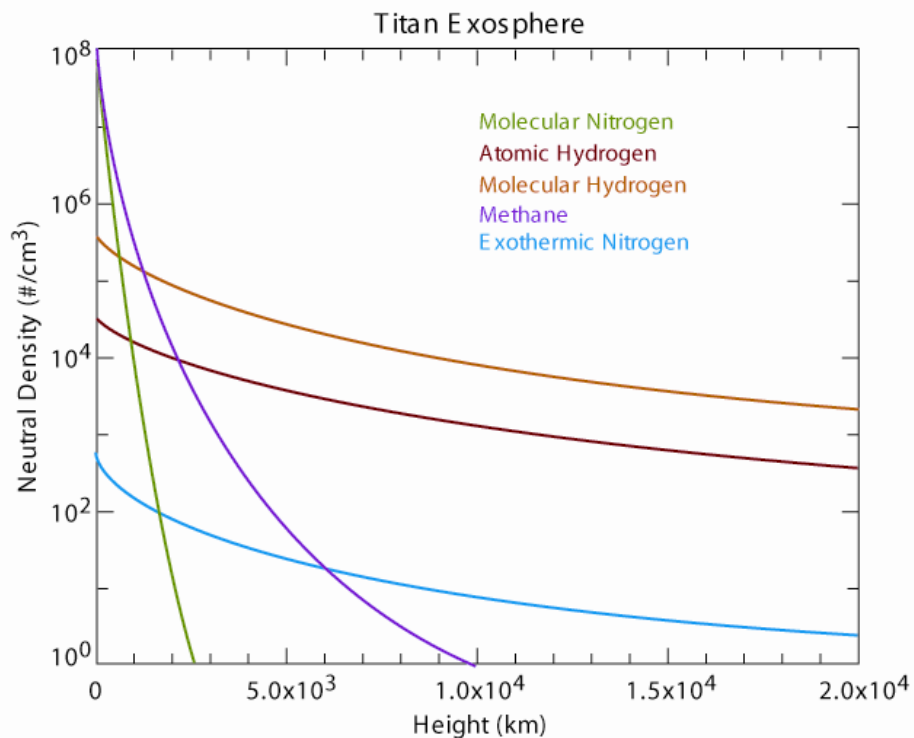


Figure 4.

We have developed an improvement of the exosphere model originally presented by Hartle and coworkers [1]. The original model only had atomic hydrogen, H, and molecular nitrogen, N_2 . As described in [17, 18, 19 and 20], we have added H_2 and CH_4 as important constituents to Titan's exosphere. Furthermore, we have added the ejection of suprathermal nitrogen atoms, due to electron and photon excitation of N_2 [21, 22 and 23] and sputtering due magnetospheric ion impact [24, 25, 26 and 27], to our exospheric model calculations. The results are shown in Figure 4, where we have used a spherically symmetric model for the exosphere. As can be seen far from Titan H_2 , H and N^* dominate far from Titan with H_2 an order of magnitude larger than H, while H is two orders of magnitude larger than N^* . Because methane is lighter than N_2 it will dominate for heights greater than a few hundred kilometers above the exobase at $r \sim 4000$ km, until a height ~ 1500 km when H_2 starts to dominate. Note that the mass density of CH_4 will dominate over that of H_2 for heights up to 2500 km. This will be important when considering mass loading calculations. Finally, when within a few scale heights of the exobase, N_2 will dominate over everything else, especially its mass density. These exospheric calculations show that Titan's exosphere extends to heights greater than 10,000 km and the H, H_2 and N^* will form a large neutral torus around Saturn centered on Titan's orbital position (see [3]).

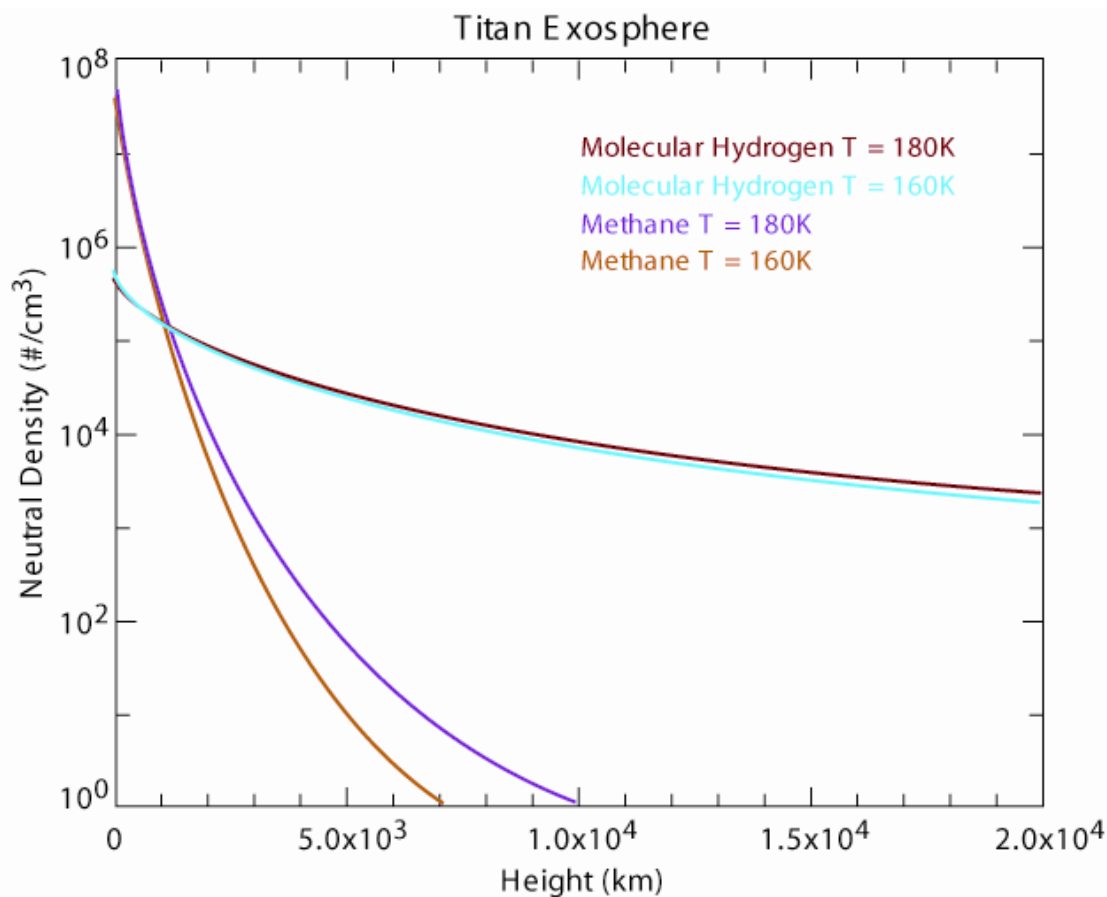


Figure 5.

3.2 Day-Night Temperature Effects

In order to ascertain day-night asymmetries in the exosphere, we compare in Figure 5 exospheric calculations with assumed exobase temperatures of 180 K (sunlit side) and 160 K (night side), using spherically symmetric calculations for each exosphere while retaining the same exobase densities. We have done this for H₂ and CH₄. As can be seen there is very little difference between radial profiles for H₂ because of its high escape velocity, while for methane, inside a height of 2000 km, the neutral density on the day side can be ~ a factor of 5 greater than that on the night side. This effect would be further accentuated if night side temperatures were ~ 150 K or lower. These results further demonstrate the importance of developing a 3D model of Titan's exosphere. Therefore, we feel that further hybrid code simulations of the Titan interaction should include a 3D exosphere in model calculations. This is under-scored by the fact that the heavy neutrals, such as methane and N₂, will dominate the mass loading of the incoming ambient plasma during its interaction with Titan's upper atmosphere and exosphere.

4.0 MASS LOADING CALCULATIONS: IONOPAUSE LOCATION?

Using the exosphere model described in the preceding section, we will compute the effects of mass loading on the flow of the ambient plasma due to pickup ions as described in [1]. As discussed above the exosphere will include H, H₂, N*, CH₄ and N₂. We include photoionization, and electron impact ionization in our model calculations. The equations used for our mass loading calculations are given in Equations 1-4.

$$P = \nabla \cdot N\vec{V} = (N_e V_e \sigma_1 + J)n + NV_e' \sigma_1 n, \quad (1)$$

$$\Delta V_i = -2 \int_{\ell_i}^{\ell_{i+1}} \frac{[m_H K_H n_H + m_{N_2} K_{N_2} n_{N_2} + m_{H_2} K_{H_2} n_{H_2} + m_{CH_4} K_{CH_4} n_{CH_4} + m_{N^*} K_{N^*} n_{N^*}]}{\rho_i}, \quad (2)$$

$$V_{i+1} = V_i + \Delta V_i, \quad (3)$$

$$\rho_{i+1} = \rho_i + \int_{\ell_i}^{\ell_{i+1}} \frac{d\rho}{dt} \frac{ds}{V_i}, \quad (4)$$

Equation 1 is the continuity equation for a particular ion species, where the ion production rate terms are on right hand side. For our calculations we will ignore, to first order, the compression or expansion of flux tubes, which is expected to occur as the ambient plasma interacts with Titan's upper atmosphere and ionosphere. We do take into account the added contribution of secondary electrons (i.e., $T_{\text{sec}} \sim 2$ eV for photoelectrons), which turns out to be a small correction. Equation 2 is the integral representation of an ion velocity component along a stream tube, showing the decrease in flow speed due to the effects of mass loading. The parameter, K_i , gives the production rate of a particular ion species due to the various reaction rates discussed above. We note that in the case of charge exchange reactions (not included here) between ambient N⁺ and H or H₂, the net effect is to reduce the mass loading of the plasma flow, while charge exchange reactions between H⁺ and CH₄ or N₂ will increase the mass loading of the

plasma flow. In order to do this calculation correctly, one must consider the fact that ambient ions that are lost are quickly replaced by the large reservoir of ambient ions distributed along a flux, whose dimensions can be several Saturn radii long. The emptying of a flux tube is not expected to be important until the guiding center of the ion is within one gyroradius of the exobase. Equations 3 and 4 show how we compute the decrease of the plasma flow and build up of the ion mass density of the flow as an integral along the streamline. Finally, we emphasize that our calculations are fluid-like and do not take into account finite gyroradius effects. To first order this is not a bad approximation, since the plasma is slowing down as it approaches Titan and the flow is becoming more fluid-like when it gets near the ionopause.

In Figure 6 we show the geometry for our calculations with a fluid element moving past

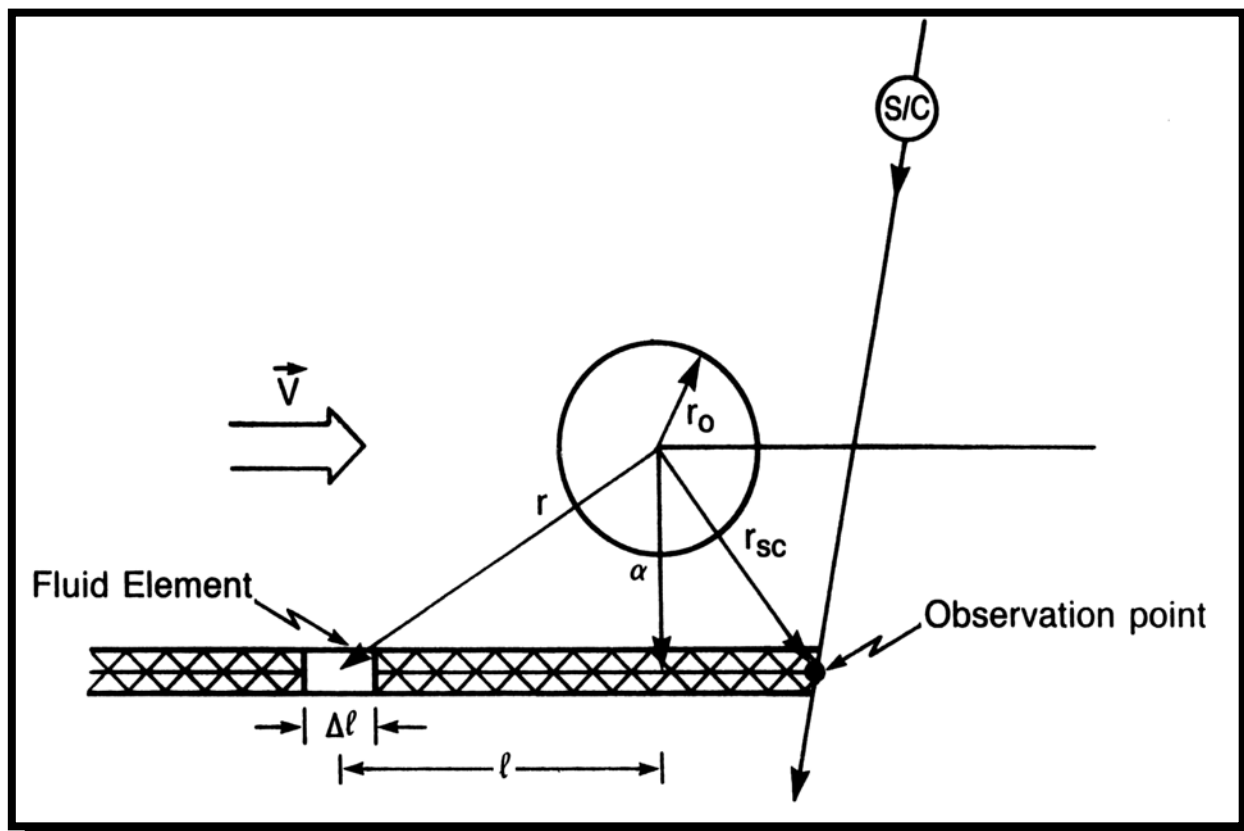


Figure 6.

Titan with impact parameter $b=\alpha$. In these calculations we are ignoring deflections and compressions/expansions of the fluid element as it moves past Titan. In the case of zero impact parameter, $b=0$, the fluid element moves along the x-axis toward Titan. When mass loading becomes very large the plasma will stop at a boundary called the “ionopause”. In Figure 7 we show the reduction in flow speed along a streamline with impact parameter $b = 0$, where considerable deceleration occurs between 5500 km and 6000 km. In [1], they estimated the “ionopause” to be at ~ 4400 km. In the case of $b = 0$ we estimate the “ionopause” location to be ~ 4800 km. The addition of methane, which extends to larger distances than N_2 , evidently accounts for the differences between the

two calculations. At an impact parameter of $b = 6000$ km, the flow speed decreases considerably before it asymptotes to ~ 60 km/s as it moves past Titan. Considering Figure 2 and Table 2, we would argue that this calculation pertains to spectrum 2, where the pickup ion is CH_4^+ with a drift speed of ~ 50 km/s. In the case of $b = 5500$ km, the flow speed decreases to an asymptotic value ~ 5 km/s as the fluid element moves past Titan. If the “ionopause” is ~ 4800 km, spectrum 4 is consistent with this calculation for which Table 2 shows the drift speed to be ~ 5 km/s for pickup N_2^+ . For lower impact parameters the flow decreases rapidly. Under these circumstances, the flow must be moving tangent to the “ionopause” boundary.

We emphasize that our calculations have ignored the effects of the upstream plasma pressure, magnetic field pressure and magnetic tension, all of which will tend to move the ionopause to a lower altitude. For $b = 0$, we estimate the mass loading force to be $F_{\text{ML}} \sim 4.5 \times 10^{-11}$ dyne/cm² at the nose of the “ionopause”, while the upstream magnetic field pressure will be $F_{\text{M}} = B^2/8\pi \sim 10^{-10}$ dyne/cm² for a field strength $B \sim 5$ nT. The total upstream plasma pressure $p \sim 10^{-9}$ dyne/cm², with plasma beta $\beta \sim 11$ as reported by [7]. Therefore, $p \gg F_{\text{M}} > F_{\text{ML}}$ and mass loading alone will probably not define the actual position of the ionopause or its thickness. The model calculations by [28] give an ionospheric density of $N_{\text{ion}} \sim 2000$ ions/cm³ at an altitude $z \sim 1000$ km or $r \sim 3600$ km. If we impose pressure balance at the ionopause then

$$P = p + F_{\text{M}} = N_{\text{ion}} k_{\text{B}} (T_{\text{i}} + T_{\text{e}}) \quad (5)$$

$P \sim 10^{-9}$ dyne/cm² is the upstream plasma pressure and magnetic field. Ignoring a possible magnetic field in the ionosphere, we can get a pressure balance altitude of $z \sim 1000$ km if we set $T_{\text{i}} \sim 1800$ K. It is interesting to note, that this temperature is much greater than the neutral gas temperature $T \sim 180$ K of the upper atmosphere, as originally derived from the Voyager 1 observations by [29]. So, in this simple scenario, the ionopause location could reside somewhere between $3600 \text{ km} < R_{\text{ion}} < 4800$ km. However, the above argument ignores some of the well known processes in ionopause regions; i.e., slowing down by mass loading is usually accompanied by piling up of magnetic field and plasma (ambient and new born ions). The piled up field and plasma can add significantly to pressure and pressure gradient forces as discussed in [30] for Venus.

At this point, we note that although $F_{\text{ML}} \ll P_{\text{MAG}}$, the scale length for F_{ML} at the boundary where mass loading is most important (i.e., $r \sim 4800$ km and $b = 0$) is $L_{\text{ML}} \sim 100$ km, while that for P_{MAG} is $L_{\text{MAG}} \sim 1000$ km. Therefore, at this boundary mass loading could dominate over pressure gradients and there could be a sudden drop in flow speed at this boundary. Inside this boundary inward motion of the plasma to the ionosphere would be dominated by pressure gradients in the plasma. These calculations also indicate that there could be considerable mixing of the magnetospheric plasma with Titan’s upper atmosphere for $3600 \text{ km} < r < 4800$ km (see discussions in [9]). These features of the interaction are similar to that calculated by [8], who used a 2D MHD code. They found a similar location and thickness of this ionopause layer estimated here, $3600 \text{ km} < r < 4800$ km, and confirms the general validity of our calculations. But, as

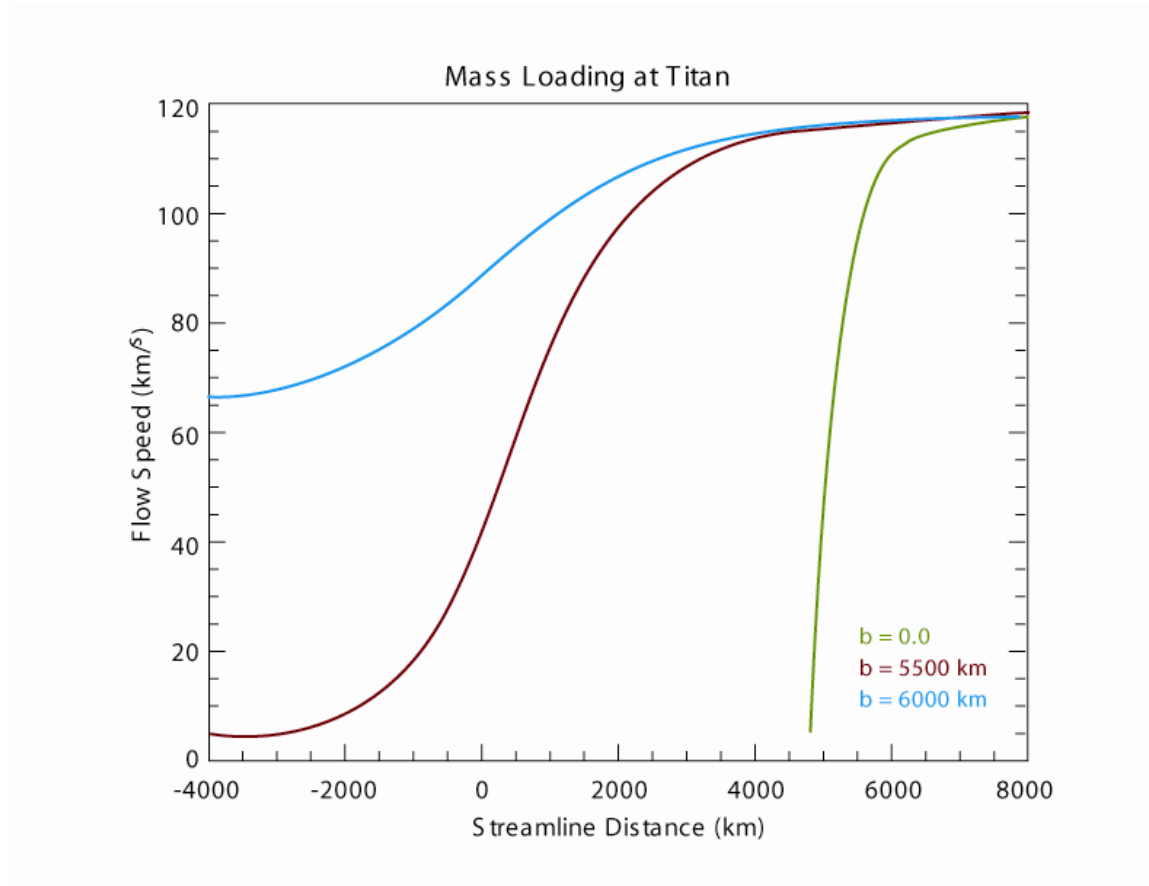


Figure 7.

previously emphasized, the ability to properly characterize this boundary one must use a hybrid code similar to that developed by [9] at high altitudes, which then transitions to an MHD calculation at lower altitudes where the flow is more fluid like. One also expects the thickness of the ionopause to be \sim an ion gyroradius, which for Titan could be several hundred kilometers thick as suggested by our previous arguments.

Reference [23] used similar arguments originally presented by Hartle and coworkers [1] to put the ionopause at $R_{\text{ion}} \sim 4400$ km. If true, their result would prevent the magnetospheric plasma from having access to Titan's upper atmosphere and thus downgrade the importance of the exothermically produced nitrogen atoms with regard to the nitrogen torus surrounding Saturn. They estimated that the source strength for the escaping N atoms would be reduced from $S_N \sim 3 \times 10^{26}$ atoms/s as originally proposed by [21] to be $S_N \sim 10^{25}$ atoms/s. If the ionopause is rather at $r < 4400$ km, then the source term for exothermically produced nitrogen could be considerably greater. References [22] and [3] discuss these issues in more detail.

Because the upstream plasma and magnetic field can have pressures large compared to ionospheric pressures without heating, the ionosphere could be highly compressed with a correspondingly thick ionopause residing between 3600 km and 4800 km. Reference [2] discussed a similar situation for Triton, where they made analogies with Venus'

ionosphere. Under these circumstances energetic electrons will tend to gradient drift around Titan and not have direct access to its upper atmosphere for altitudes less than 1000 km. This could have an important effect on models of Titan's ionosphere, such as that by [28].

5.0 SUMMARY and CONCLUSIONS

We reviewed the original observations of the Voyager 1 flyby with Titan as reported by Hartle and coworkers [1]. As the Voyager 1 spacecraft approached Titan we observed evidence for pickup ions in the ion spectra, for which, the pickup ions could either be H^+ or N_2^+ . We then improved the neutral exosphere model used by [1], by adding H_2 , CH_4 , N^* , to the original species H and N_2 . This was based on theoretical developments that occurred after the original work by [1]. We then presented new interpretations of the Voyager 1 plasma and magnetic field data, where we showed evidence of finite gyroradius effects upon the ambient plasma. We showed that the ambient plasma was preferentially lost on the side where pickup ions were observed. This was consistent with the viewing geometry of the plasma instrument's four sensors and the spacecraft position along its track past Titan. Basically, for the D cup to see ambient ions for spectrum 2, the ion guiding centers had to be offset toward Titan relative to the spacecraft and thus had a greater probability of encountering Titan's upper atmosphere, while on the outbound pass the reverse was true. A similar effect was suggested by the hybrid calculations of [9], but they gave no reason for the effect.

We showed that mass loading could be important at Titan, but since the plasma pressure of the upstream flow can dominate the mass loading term, mass loading alone cannot determine the position of the ionopause location or its thickness. We then compared our mass loading calculations with the plasma ion spectra and showed that the pickup ions in spectrum 2 was consistent with CH_4^+ , but there may also have been some evidence of heavy ions being picked up somewhere upstream and then observed by the plasma instrument at energies ~ 5 keV (i.e., ion gyroradii ~ 7800 km). We then showed that spectrum 3 was probably CH_4^+ , but N_2^+ could not be ruled out. Finally, spectrum 4 was very likely N_2^+ . This is a revision of the original analysis by Hartle and coworkers [1], where they proposed that H^+ was the likely pickup ion for spectra 2 and 3. But this was before they were aware of an intermediate neutral such as CH_4 ([17], [18], [19] and [20]) for the exosphere of Titan.

We also looked into the importance of the day-night asymmetry in the exosphere. We assumed an exobase temperature on the dayside of $T_{\text{exo}} \sim 180$ K and a night side value $T_{\text{exo}} \sim 160$ K. In the case of H and H_2 there was very little variation with temperature, while for CH_4 there was a significant difference for altitudes $z > 2400$ km where mass loading effects are important. This suggested the need to for a 3D exosphere model, similar to the one originally developed by [13], [14] and [15]. Such a model would include both latitude-longitude maps of temperature and winds at the exobase for the various neutral species. Further improvement could be obtained with the use of a thermosphere general circulation model to fix the exobase boundary conditions; i.e., temperature and wind variations in latitude-longitude.

Pressure balance calculations indicate that the ionopause region could lie between 3600 km and 4800 km. Such a “thick” ionopause implies that the source term for the ejection of suprathermal nitrogen atoms could be considerably greater than present estimates $S_N \sim 4.5 \times 10^{25}$ atoms/s (see [3]). However, if plasma and magnetic field pressures and gradients could be included in future models, they would have the tendency to reduce the thickness of the ionopause.

In order to properly characterize the interaction with Titan one must use a hybrid code at high altitudes similar to that used by [9], which transitions to an MHD like plasma at lower altitudes. As discussed, even though $F_{ML} \ll P_{MAG}$, the scale length for F_{ML} is $L_{ML} \sim 100$ km, while that for P_{MAG} is $L_{MAG} \sim 1000$ km. Therefore, at the boundary where mass loading is important at $r \sim 4800$ km, mass loading could dominate over pressure gradients and there could be a sudden drop in flow speed at this boundary. Inside this boundary inward motion of the plasma would continue because of pressure gradients in the plasma and produce a “thick” ionopause layer similar to that calculated by [8]. These calculations indicated that there could be considerable intermixing of the magnetospheric plasma with Titan’s upper atmosphere for $r < 4800$ km (see discussions in [9]). Reference [2] modeled a similar situation for Triton where they showed that electrons with $E \sim 50$ keV or less would tend to gradient drift within the ionopause layer and not have direct access to the moon’s lower atmosphere. A similar situation may apply for Titan.

Upstream of the mass loading region ($r > 4800$ km) pressure gradients as described by [9] could slow down the plasma. This result is consistent with Voyager 1 observations.

Finally, we would like to close by making some comments about what kind of an interaction might occur in Saturn’s magnetosheath or the solar wind. If Titan enters the magnetosheath the flow would be dominated by protons, with flow speeds ~ 400 km/s and it would be transonic. We would expect this to happen during a compression region with flow speeds in the solar wind higher than average (see [31]). The density and magnetic field in the sheath could be a factor of 8 higher than typical solar wind values or $n_p \sim 0.4$ ions/cm³ and $B \sim 4$ nT which is close to that for the Voyager 1 encounter with Titan. The plasma beta would be $\beta \sim 2$, the Alfvén speed $V_A \sim 138$ km/s and $M_A \sim 2.9$. The pickup energies for CH_4^+ could be as high as 50 keV for $V \sim 400$ km/s and the gyro-radii would be $r_g \sim 15000$ km, while the gyro-radii for the ambient protons would be $r_g \sim 1000$ km. So, in many ways the interaction would be similar to that observed in the magnetosphere, except for the differences in composition of the ambient ions and higher flow speeds. In the solar wind, the conditions would be similar since the compression of the magnetosphere would be greater and ambient density and field strengths would also be greater. But, the flow speeds could be $V \sim 600$ km/s, the interaction would be supersonic (i.e., shock is expected) and pickup energies for CH_4^+ could be as high as $E_{pu} \sim 100$ keV and the gyro-radii for pickup ions $r_g \sim 45000$ km, which is much greater than the size of Titan. So, we would expect to see a more extended interaction region than that observed within Saturn’s magnetosphere. In fact, the interaction would be more like a comet.

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FIGURE CAPTIONS

Figure 1. Shows the Voyager 1 Titan flyby geometry on November 12, 1980. The figure shows the corotational wake, the spacecraft trajectory, the sensor alignment for the encounter and the location of the eight ion spectra recorded by the plasma instrument. See text for details.

Figure 2. Titan interaction as envisioned by Hartle and coworkers [1]. Exobase and ionopause locations are indicated, as well as inferred stream lines and pickup ion trajectories. See text for details.

Figure 3A. Plasma instrument ion spectra 1 to 4 for sensors A, B, C and D. The x-axis is log of ion energy-per-charge and ordinate is the log of the ion reduced distribution function. Location of ion spectra indicated in Figures 1 and 2.

Figure 3B. Same as Figure 3A except here we show ion spectra 5 to 8.

Figure 4. Titan's neutral exosphere which is composed of H, H₂, CH₄, N₂ and N^{*}. Here we used a spherically symmetric exosphere, the exobase was assumed to be at 4000 km and used an exobase temperature of 160 K.

Figure 5. Titan's neutral exosphere for H₂ and CH₄ assuming a day-night exobase temperature difference of 180 K and 160 K, respectively. See text for details.

Figure 6. Shows geometry of mass loading calculations with fluid element shown as it accumulates pick up ions and are then observed at the spacecraft position which is downstream from the flow.

Figure 7. Shows the slowing down of the ambient plasma due to the accumulation of pickup ions and corresponding mass-loading. Solutions are shown for impact parameters $b = 0, 5500 \text{ km}$ and 6000 km .

