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Ion distributions of 14 amu pickup ions associated with Titan's plasma interaction

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[1] Titan has an extensive ionosphere consisting of ions of nitrogen and a variety of hydrocarbons that can be picked up by Titan's interaction with the surrounding plasma. Usually Titan is within Saturn's magnetosphere, however, there may be times when Titan exits the magnetosphere and interacts directly with the solar wind. We compare and contrast ion kinetic energy and spatial distributions of 14 amu pickup ions from hybrid simulations of Titan's plasma interaction with both Saturn's magnetosphere and the solar wind. These results can be compared with ion spectrometer measurements to be made during the upcoming Cassini mission. *INDEX TERMS:* 2152 Interplanetary Physics: Pickup ions; 2459 Ionosphere: Planetary ionospheres (5435, 5729, 6026, 6027, 6028); 2732 Magnetospheric Physics: Magnetosphere interactions with satellites and rings; 2780 Magnetospheric Physics: Solar wind interactions with unmagnetized bodies. **Citation:** Ledvina, S. A., S. H. Brecht, and J. G. Luhmann (2004), Ion distributions of 14 amu pickup ions associated with Titan's plasma interaction, *Geophys. Res. Lett.*, *31*, L17S10, doi:10.1029/2004GL019861.

1. Introduction

[2] The only data available on Titan's interaction with Saturn's magnetosphere were obtained on a single flyby by Voyager 1 [cf. *Neubauer et al.*, 1984, and references therein]. Voyager 1 passed through Titan's wake at a distance of 6969 km (2.7 R_T where R_T = 2575 km) while it was in Saturn's outer magnetosphere. The incident plasma was found to have sonic, Alfvénic and magnetosonic mach numbers of 0.57, 1.9 and 0.55 respectively. The incident convection electric field accelerates ions in the ionosphere removing them from Titan. This pickup process represents an important loss mechanism to the ionosphere and upper atmosphere. The loss rate has been estimated by *Eviatar et al.* [1982] to be about 3×10^{24} ions/s.

[3] Titan's plasma environment is highly variable. The position of Saturn's bow shock depends on the incident solar wind conditions and has been observed to vary typically between 23.6 to 31.5 R_S. Under extreme solar wind conditions Pioneer 11 observed the position of the bow shock near 20 R_S [*Schardt et al.*, 1984]. Titan's orbit in the outer magnetosphere at 20 R_S means that there is a chance that Titan may interact directly with the solar wind or the magnetosheath plasma when it is near noon Saturn local time. In addition local variations within Saturn's magnetosphere can lead to very different plasma conditions along Titan's orbit [cf. *Wolf and Neubauer*, 1982; *Schardt et al.*, 1984; *Hansen*, 2001]. Titan's interaction with its surrounding plasma environment has been studied by several simulation methods including: test-particles, 1, 2 and 3-dimensional MHD simulations and hybrid simulations [cf. *Ledvina et al.*, 2004, and references therein].

[4] In this paper the kinetic energy and spatial distributions of 14 amu pickup ions near Titan are examined using self-consistent hybrid simulations. The plasma conditions representative of the Voyager 1 flyby and typical solar wind conditions near Saturn are used in this study. The results can be used for comparisons with ion spectrometer measurements soon to be obtained during Titan flybys of the Cassini orbiter. The magnetic field structure for these conditions, as well as the magnetic field vectors and contours of the magnetic field strength, has been reported by *Ledvina et al.* [2004].

2. Simulations

[5] The simulations are performed using the HALFSHEL hybrid (fluid electrons, kinetic ions) simulation code. This is the same simulation code previously used to simulate Titan by *Brecht et al.* [2000] and *Ledvina et al.* [2004] as well as Mars [cf. *Brecht*, 1997, and references therein]. This simulation tool treats the electrons as a charge neutralizing massless fluid, retains the full kinetic behavior of the ions and treats the particles and fields self-consistently. Further details about the basic assumptions made in the hybrid simulation formalism are given by *Brecht and Thomas* [1988] and *Harned* [1982].

[6] Retaining the full kinetic behavior of the ions gives hybrid simulations some distinct advantages over fluid/MHD simulations of plasma interactions. The Hall term is neglected in most MHD simulations and hence they do not display diamagnetic effects. Most MHD simulations only use a single momentum equation and hence cannot simulate counter streaming. Also most MHD approximations are closed with the ideal gas law, implying that the plasma is described by a Maxwellian distribution function. This is not

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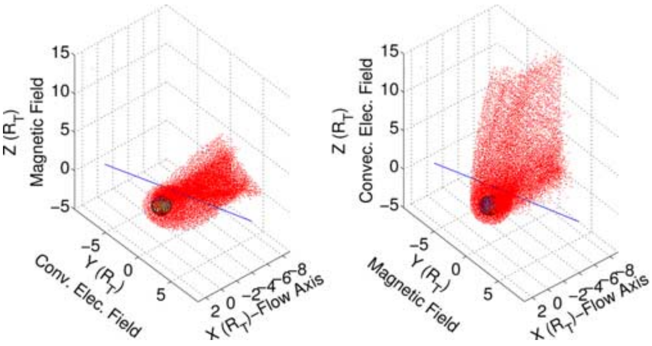

Figure 1. A sample of the 14 amu pickup ion positions in the magnetospheric case (left) and the solar wind case (right) are shown. In both cases the incident plasma flow is along the negative x-direction. In the magnetospheric case the incident magnetic field is along the negative z-direction, the convection electric field points along the y-axis away from Saturn. In the solar wind case the incident magnetic field is along the y-axis and the convection electric field is along the z-axis. Saturn is in the direction of the flow.

a limitation for the ions in hybrid simulations. Furthermore, the kinetic formalism of the hybrid simulations does not limit the pressure to being an isotropic scalar. The fluid nature of the MHD simulations cannot account for the collective gyroradii effects that are present in the plasma. However, these fluid assumptions make MHD simulations better suited for simulating an ionosphere and its associated chemistry, where the higher plasma densities, lower ion temperatures and smaller ion gyroradii ensure that the plasma can be described by a Maxwellian distribution function.

[7] The two conditions simulated in this work are representative of the extremes that Titan may find itself encountering. As such, they provide some bounds as to the pickup ion distribution spatial and energetic attributes. It is these two situations that are discussed in the remaining portion of the paper.

[8] The upstream plasma conditions used for the simulation of Titan with Saturn's magnetosphere are representative of the Voyager encounter except the ions are injected cold (i.e., they have no thermal speed) at the upstream boundary. New ions are injected at the boundary when the previous ions cross the first grid cell. The choice of a cold injection is predicated on several considerations: one is numeric and the other physical. The numerical consideration is that it is difficult to have "inflow" boundary conditions and have ions flowing out of this boundary, as would be the case if the reported ion temperature and resultant thermal speed were loaded into the simulation. Further, there is some doubt on the part of the authors that a "magnetic tail structure" such as reported by *Ness et al.* [1982] would exist at the temperatures reported. Further hybrid simulations need to be performed in order to better understand the effects finite ion temperatures have on Titan's plasma interaction.

[9] A region of 15 $R_T \times 30\ R_T \times 17.5\ R_T$ was covered with a resolution of $66 \times 153 \times 91$ cells. The resulting cell size was about 500 km, which was chosen to be consistent with the initial MHD simulations of *Ledvina and Cravens* [1998], before their Voyager case was redone with variable gird spacing. The upstream species was taken to be N^+ with a drift speed of 125 km/s toward Titan. We neglect the magnetospheric H^+ component since N^+ carries most of the momentum. The ionospheric species (also N^+) was loaded to maintain 10% of the peak density profile from the simulation of *Keller et al.* [1992] (a detailed explanation of how the ionosphere is simulated and the reasoning behind the approximations used are given by *Brecht et al.* [2000]). The peak of the ionosphere was located at an angle of 60° with respect to the incident flow with a cosine fall off. The upstream magnetic field had a magnitude of 5.1 nT and was oriented perpendicular to Titan's orbital plane. This simulation used 3.6×10^6 particles to represent the magnetospheric N^+ and 1.9×10^5 particles to represent the pickup N^+.

[10] For the solar wind interaction simulation the grid resolution was increased to $128 \times 257 \times 150$. This reduced the cell size to about 300 km. The ionosphere was loaded in the same fashion as the magnetospheric case except the ionospheric peak coincided with the incident flow (i.e., 0°). The upstream species was taken to be H^+ with a number density of 0.1 cm^{-3} and a flow speed of 450 km/s. The incident magnetic field strength was 0.5 nT and was oriented in the ecliptic plane. The solar wind H^+ was represented by 19.7×10^6 particles, 8.9×10^5 particles represented the pickup N^+. These conditions are representative of the solar wind conditions near Saturn. We use these solar wind values as a first approximation since the location of Saturn's bow shock as a function of solar wind conditions is not known. The results for this simulation are qualitatively correct but quantitatively they would be expected to be more extreme for solar wind conditions that would move the bow shock location inside of Titan's orbit. The details of the boundary conditions are given by *Ledvina et al.* [2004] and *Brecht et al.* [2000].

3. Results

[11] A sampling of the pickup ion positions for each simulation can be seen in Figure 1. In both simulations the incident flow is antiparallel to the x-axis. The incident magnetic field is antiparallel to the z-axis in the magnetospheric case and parallel to the y-axis in the solar wind case. The resulting convection electric field in the magnetospheric case is parallel to the y-axis, and parallel to the z-axis in the solar wind case. Also shown in the figure is the trajectory of Voyager 1. Examining the ion positions it is easy to see that the convection electric field pulls the ions away from the hemisphere along the direction of the convection electric field. Ions picked up on the other hemisphere are drawn into the wake region and move tailward. In the wake there is a clear asymmetry in the ion positions with the ion density higher on the side where the convection electric field points away from the moon.

[12] The ion positions in the magnetic field-flow-plane for each simulation are shown in Figure 2. Note these planes in top and bottom panels are spatially perpendicular to each other. The ions are color coded with the log of their kinetic energy. In both cases the convection electric field points out of the plane of the figure. The ions are distributed symmetrically about the flow axis. In the near Titan region (within

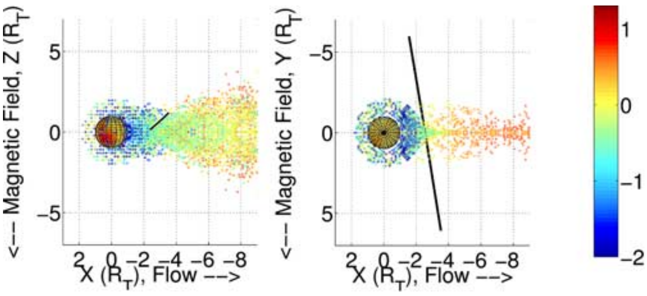

Figure 2. Sample 14 amu pickup ion positions in the flow-magnetic field plane for the magnetospheric case (left) and the solar wind case (right). The ions are color coded by the log of their kinetic energy (keV).

about 2 R_T) the ion population is dominated by low energy ions (less than 300 eV). The kinetic energy of the ions within the wake region increases with their distance from Titan. An ion focal point exists in both simulations, around 3.5 R_T (left panel) and 7.5 R_T (right panel). Downstream of this focal point the ions begin to scatter along the direction of the unperturbed magnetic field.

[13] The ion positions in the convection electric field-flow planes are shown in Figure 3. The view shows ions being pulled from Titan and from the tail. The ions are then accelerated up to large kinetic energies (up to 20 keV in the solar wind). It is important to note that these ions leave our simulation domain. In the solar wind their kinetic energy would be up to 60 keV. In both simulations the most energetic ions exist on the leading edge of the tail flare (the side where the electric field points away from Titan). The ions on the opposite side of the tail (where the electric field points toward Titan) have energies around 1 keV. The region within 1–2 R_T of Titan is mainly filled with low energy ions, though there is a significant population of medium energy ions in the magnetospheric case. Notice the high population of low energy ions in the near wake region of the southern pole of the solar wind simulation (right panel). The fields are pushing the ions around Titan into the geometric wake. A similar process is occurring in the magnetospheric simulation though it is not as pronounced due to the weaker fields.

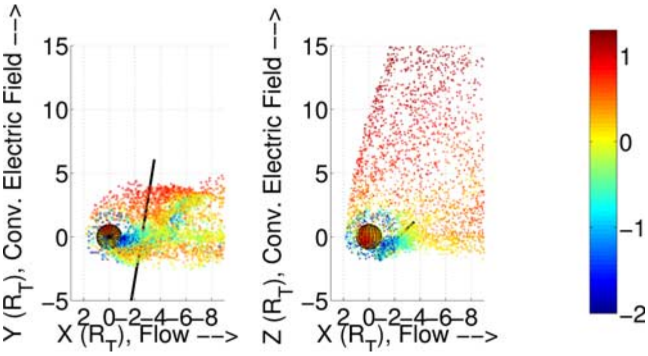

Figure 3. Sample 14 amu pickup ion positions in the flow-convection electric field plane for the magnetospheric case (left) and the solar wind case (right). The ions are color coded by the log of their kinetic energy (keV).

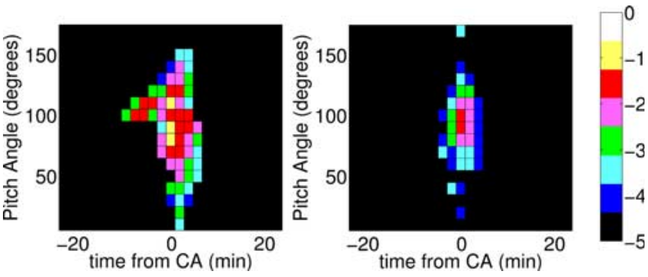

Figure 4. Simulated pitch angle distributions sampled along the Voyager 1 trajectory for the magnetospheric case (left) and the solar wind case (right). Time from closest approach is plotted versus pitch angle. The log of the particle density (cm^{-3}) is indicated by the color.

[14] Simulated pitch angle distributions of pickup ion sampled along the Voyager trajectory for each simulation are shown in Figure 4, where time from closest approach is plotted versus the pitch angle. The colors indicate the log of the pickup ion density (cm^{-3}). The trajectory crosses the asymmetric portion of the tail in the magnetospheric case (left panel). The ions are near the apex of their cycloidal trajectories. This is reflected in the pitch angle plot by the flux of ions with pitch angles around 90° that show up at ten minutes from closest approach. Near closest approach the pitch angles are not evenly distributed about 90° in this case. This is because the trajectory does not equally sample both magnetic tail lobes [cf. *Ledvina et al.*, 2004; *Ness et al.*, 1982]. Since the ions will be moving away from Titan the direction of the tail field is reflected in the pitch angle plots. This is not the case in the solar wind simulations since the trajectory more evenly samples the magnetic lobes.

[15] Simulated ion spectrograms along the trajectory of Voyager 1 are shown in Figure 5 where the time from closest approach is plotted versus the ion energy in keV. The colors indicate the log of the pickup ion density (cm^{-3}). In the magnetospheric case (left panel) the spacecraft crosses the asymmetric portion of the tail. The spacecraft enters the tail structure where the pickup ions have been accelerated away from Titan. This is reflected in the spectrogram by the high ion kinetic energy and low ion flux beginning at 10 minutes from closest approach. These ions are near the apex of their cycloidal trajectories. The spacecraft then samples the higher density lower energy ions in the tail

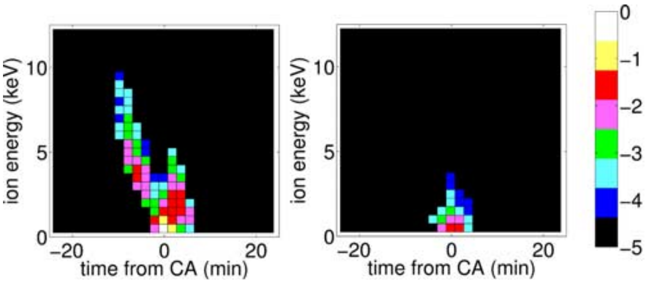

Figure 5. Simulated spectrograms for ions sampled along the Voyager 1 trajectory for the magnetospheric case (left) and the solar wind case (right). Time from closest approach is plotted versus kinetic energy; the log of the pickup ion density (cm^{-3}) is indicated by the color.

region behind Titan and exits the tail structure. The ion signature is asymmetric with respect to the time of closest approach since the ion signal is lost about 6 minutes after closest approach. This is a result of the trajectory being closely aligned with the plane of the convection electric field.

[16] In contrast the ion tail signature in the solar wind case is more symmetric about closest approach, since the trajectory crosses nearly perpendicular to the plane that contains the convection electric field. In addition the trajectory crosses the tail structure near Titan before the ions have a chance to exit the tail fields and get picked up by the solar wind. Hence the ions have relatively low kinetic energies. The pickup ions in the solar wind case are much more energetic than in the magnetospheric case, but this trajectory doesn't sample them. Thus many flyby trajectories are needed to characterize the pickup ion distributions.

4. Conclusion

[17] Based on these simulations several conclusions about pickup ion behavior near Titan can be reached.

[18] 1. The lowest energy ions exist within a radial distance of 1–2 R_T. These ions are produced primarily on the dayside by photoionization but they exist even on the night side hemisphere because of their redistribution by the electric and magnetic fields.

[19] 2. The ion distributions are symmetric about the flow axis in the plane that is perpendicular to the convection electric field. A focus point exists in this plane along the tail axis. Downstream of this point the ions spread along the direction of the incident magnetic field. The addition of a finite temperature to the magnetospheric flow will likely produce some spreading of the pickup ion distributions.

[20] 3. In the plane that contains the convection electric field the ions are accelerated in the direction of the field and are not distributed symmetrically about the flow axis.

[21] 4. In the tail region near Titan the ions are spatially segregated by energy. As the pickup ions move down the tail they gain energy and are no longer segregated.

[22] 5. Simulated spectrograms derived from the pickup ions illustrate the sensitivity of the instrument response to the trajectory of the spacecraft. This implies that numerous flybys of Titan are needed to properly characterize the nature of the tail structure.

[23] The orientation and strength of the upstream magnetic and convection electric fields have a large effect on the motion of the pickup ions and their energy. Numerous flybys of the Cassini spacecraft will be needed in order to characterize spatial and temporal ion structure of Titan's tail. Cassini will first flyby Titan in October of 2004. The INMS, CAPS and MIMI instruments on the Cassini spacecraft [cf. *Waite et al.*, 2004; *Young et al.*, 2004; *Krimigis et al.*, 2004] will be needed to provide information about the distributions of Titan's pickup ions, with supporting data from the magnetometer and Langmuir probe.

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