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Titan's ion exosphere wake: A natural ion mass spectrometer?

J. G. Luhmann

Space Sciences Laboratory, University of California, Berkeley

Abstract. According to one possible picture of the Titan atmosphere interaction with Saturn's magnetosphere, newborn exospheric pickup ions may exhibit a marked asymmetry with respect to the corotation wake due to their large gyroradii in the local ~5 nT magnetic field. These finite gyroradius effects should persist until the ions are scattered by wave-particle interactions (a scale length that is presently unknown). To the extent that simple test-particle-like motion is maintained, the combination of the small (on the scale of most ion gyroradii) size of Titan and the small, steady local magnetic field at ~20 Saturn Radii provides a natural ion mass spectrometer configuration. The resulting spatial dispersion of the pickup ion trajectories can be used for both analyzing the composition of the Titan exosphere and determining the ionization rates of its various constituents. Possible evidence of this ion mass spectrometer effect may be visible as a magnetic field perturbation in the Voyager 1 Titan flyby data.

Introduction

Our information about Titan's atmosphere is currently limited to what we have learned from the combination of remote sensing (spectroscopic) observations and one flyby by Voyager 1 in 1980. Radio occultation results obtained on Voyager 1 set upper limits on the ionospheric density [*Lindal et al.*, 1983], while *in situ* particle and field experiments provided evidence for the creation of an ion wake of Titan due to its magnetospheric interaction [e.g., *Ness et al.*, 1982; *Hartle et al.*, 1982; *Gurnett et al.*, 1982].

It is generally accepted that the atmosphere of Titan is nitrogen dominated with methane becoming important at altitudes above ~1800 km. Recently, *Keller et al.* [1992] recalculated a photochemical equilibrium model ionosphere based on the *Yung et al.* [1984] and *Yung* [1987] models for the neutral gas composition. *Keller et al.* [1992] found (consistent with some earlier results) that the ionosphere should consist primarily of the ions H_2CN^+, $C_2H_5^+$, and CH_5^+, even though the highest production rates are for N_2^+, N^+, and CH_4^+. Ion production is chiefly by photoionization, but impact by magnetospheric electrons is significant, and of course dominant at night. The difference between the composition of the major ions produced and the ionospheric composition is the result of the chemical reactions and losses that occur following production. A more elaborate model [*Keller et al.*, 1994], including MHD effects related to the plasma interaction, exhibits the same basic properties.

During the new millenium, the Cassini Orbiter will make several dozen flybys of Titan, and the Huygens probe will penetrate the atmosphere, obtaining altitude profiles of density and composition as it descends. Planning for the Orbiter mission includes debate on how to divide flyby time between imaging, radar, and in-situ observations. From this perspective, and that of optimizing the science return from Cassini, it is useful to consider what we can learn about Titan's atmosphere from *in situ* experiments in distant locations as a result of the magnetosphere's interaction with Titan.

In this paper it is suggested that the Titan ion wake may provide a useful natural "mass spectrometer" for distant analyses of the upper atmosphere. Large gyroradii (on the scale of Titan) exospheric ions picked up by the magnetospheric corotation electric field should initially produce a broad and highly asymmetric wake of Titan in which ion beams of different masses become spatially dispersed. This ion tail greatly exceeds the corotation wake in radial dimension, potentially allowing detection up to ~9 Titan radii outside of Titan's orbit. Measurements of the ions can yield both a compositional analysis of Titan's upper atmosphere and a measure of the production rates of the various ions it deposits in Saturn's magnetosphere. Using a simplified model, it is shown that magnetic field perturbations signaling the existence of such an extended Titan ion wake may already have been detected on Voyager 1.

Titan Ion Wake: Expected Characteristics

Observations at Venus and Mars have shown that upper atmosphere ions are removed by the solar wind above a boundary called the "ionopause," around which

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most of the solar wind is deflected (e.g., see the review by *Luhmann and Bauer* [1992]). At Venus the ionopause is located where the incident solar wind pressure is balanced by the ionospheric thermal pressure, except under conditions when the latter is exceeded and induced ionospheric magnetic fields contribute. Mars is expected to be in the latter state most of the time because of its weaker ionosphere. At both planets, the effects of the solar wind pick-up and removal are seen in the eroded topside ionospheric density profiles [e.g., *Shinagawa and Cravens,* 1988; 1989]. Direct detections of atomic oxygen ions, presumably arising from this process, have been made to large (~10 planetary radii) wake distances [e.g., *Moore and McComas*, 1992; *Kallio et al.*, 1995]. There are also indications that the large gyroradii of the pickup ions produce inherent asymmetries in the wake structure. Other observations in the solar wind earthward of the new Moon suggest that even in the much simpler case of an absorbing body with only an exosphere, a detectable pickup ion wake can form [*Hilchenbach et al.*, 1992]. The peak thermal pressure of the ionosphere at Titan is comparable to or less than the external pressure of the local magnetospheric plasma flow [*Keller et al.*, 1994]. This suggests that any ionopause of Titan is probably indistinct and permeable to the plasma, making the Titan-plasma interaction somewhat like the Lunar case. Under such conditions, it is reasonable to assume that the ionosphere above the photochemically dominated region (above ~1800 km altitude) which is also above the exobase (at ~1500 km) can be scavenged. The question here concerns the attributes of this pickup ion wake based on our knowledge of the physical setting of Titan.

For Venus, Mars and the Moon, the pickup ion wake characteristics have been modeled by following the motion of test particles in specified background plasma flow and field configurations [e.g. *Luhmann,* 1990; *Moore et al.*, 1991; *Cladis et al.*, 1994]. In the cases of Venus and Mars, it is necessary to consider backgrounds describing the deflection of the shocked solar wind flow around the obstacles presented by the planets' ionospheres. In contrast, an unperturbed background field and flow is a good approximation to the Moon's surroundings in the solar wind, at least on the plasma ramside where the pickup of solar wind-sputtered ions occurs. In some respects, Titan represents an interesting compromise between these cases. The incident magnetospheric plasma flow velocity is submagnetosonic and thus does not require a bow shock for deflection [e.g. *Neubauer et al.*, 1984]. At the same time, one must consider that the Voyager 1 flyby at 2-3 Titan radii downstream showed a strongly draped induced magnetotail-like structure evidently produced by heavy mass loading of the flux tubes passing close to Titan. Nevertheless, the primary plasma and field perturbations caused by this apparent obstacle were generally confined to the flow wake region [e.g. *Hartle et al.*, 1982]. The implication is that since much of the upper atmosphere of Titan on the plasma ramside must reside on fairly unperturbed magnetospheric field lines, one can model the Titan ion wake using the relatively simple Lunar type of approach.

While there is some debate over the major source of ionization for Titan's atmosphere, photoionization and magnetospheric electron impact ionization are both considered to have an influence depending on the solar illumination angle and the altitude range. One can envision that at any time there are two "hemispherical" source regions: one that is centered on the Sun, and one that is centered on the plasma ram direction. These sources can both feed the ion pickup process. Figure 1 shows the major ion production rates on the dayside of Titan according to the model of *Keller et al.* [1994]. If mass 14 and mass 28 singly ionized ions are considered representative of the major species produced in the Titan upper atmosphere, calculations of their trajectories in the Saturn magnetosphere can give an idea of how the ionospheric wake might appear.

Numerical solutions of the single ion equation of motion ($m\frac{d\vec{v}}{dt} = q(\vec{\mathbf{E}} + \vec{v} \times \vec{\mathbf{B}})$ where m is mass, q is charge, $\vec{v}$ is the particle velocity, and $\vec{\mathbf{E}}$ and $\vec{\mathbf{B}}$ are the electric

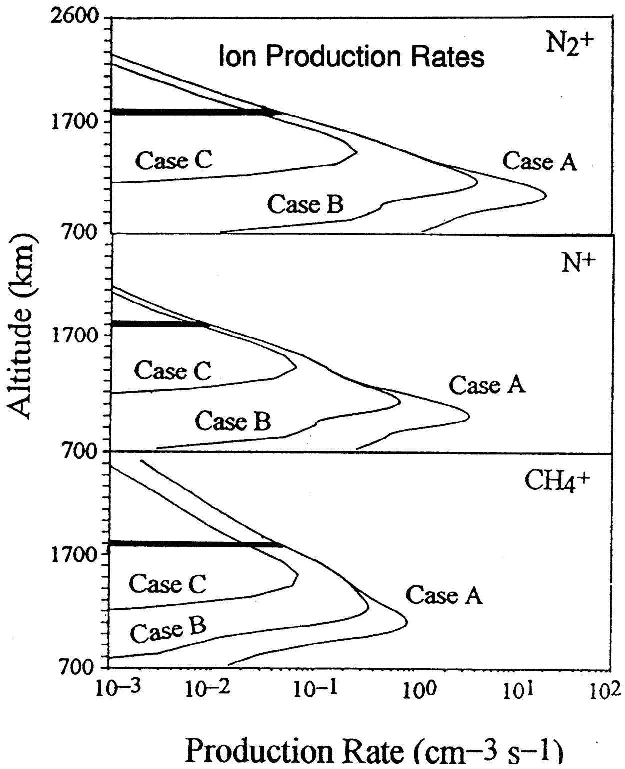

Figure 1. Titan dayside/ramside major ion production rates from *Keller et al.* [1994]. Case A includes electron impact ionization plus photoionization for a solar zenith angle of 60°. Case B is for a solar zenith angle of 90°, and case C is for impact ionization only. Case A was used here with the assumption that the methane ions' signature would closely resemble the mass 14 atomic nitrogen ions' signature and so their production rates could be merged. The added horizontal lines mark the location where the ionosphere probably ceases to be photochemically dominated (dynamics become important in determining its structure).

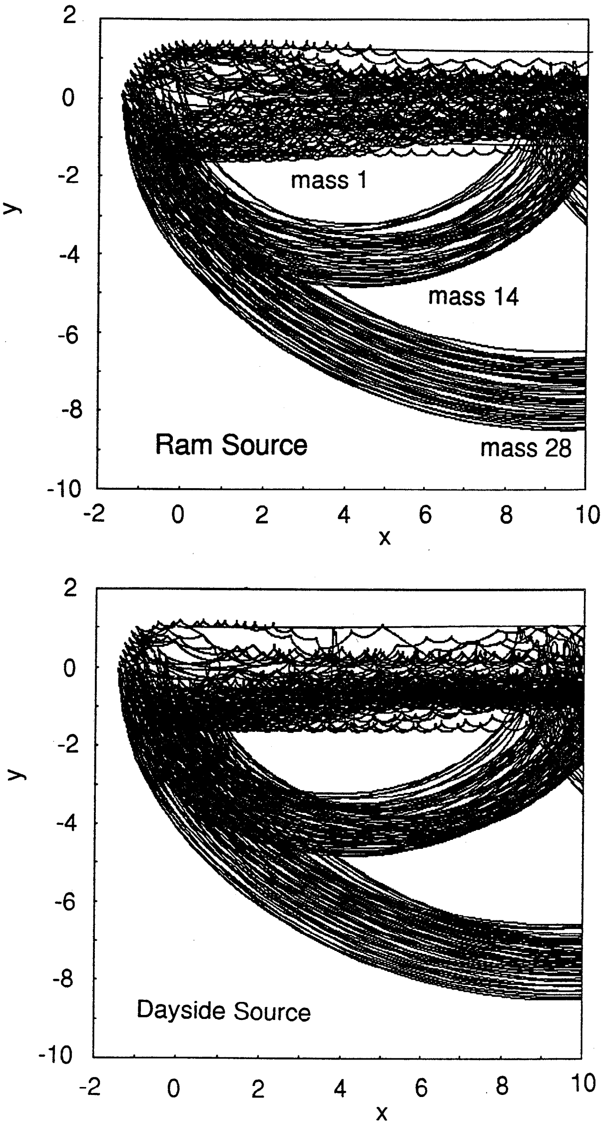

Figure 2. Calculated pickup ion trajectories for singly charged ions of mass 28, 14, and 1. Titan is at the upper left. The projection is approximately Saturn equatorial plane. The top is for a ramside hemispherical source at 1.3 R_t radius, while the bottom is for a dayside hemisphere source at the same radius.

and magnetic fields), assuming that the ions experience only the corotational electric field $\vec{E} = -\vec{V} \times \vec{B}$ associated with the $V \approx\sim 200$ km/s corotational plasma flow and the Saturn intrinsic field at the orbit of Titan, give the results shown in Figure 2. (Although Voyager 1 observed a subcorotational velocity of ≈ 150 km/s during its flyby of Titan, the usual situation is unknown and so the more idealized corotation assumption is adopted here. The results would not be substantially altered if a speed of 150 km/s had been used.) A hemispherical shell at 1.3 R_t on either the dayside or ram face was used as the source surface for illustration (R_t = Titan radius $\approx$ 2575 km). For simplicity, all ions were assumed to be "cold" (have zero energy) at their point of initiation, although newborn photo ions, for example, can have energies of tens of eV. The Titan-centered coordinate system has x along the flow axis and y in the magnetic equatorial plane. For the Voyager 1-Saturn-Sun geometry, the steady ~5 nT southward pointing ($-z$) magnetospheric field at the orbit of Titan separates the ion masses in the space outside of Titan's corotation wake. The trajectories of mass 1 ions have been included for comparison. As seen in Figure 2, the mass 1 ions with the smallest gyroradii most closely follow the flow wake, while the heavier ions execute cycloids in the equatorial plane with spatial periodicities and large radial excursions characterized by their masses. Because Titan is effectively a "point source" of the heavy ions, the trajectories are similar regardless of whether the ions are produced on the dayside or the ramside. The differences are mainly in the fraction absorbed due to impact on the satellite.

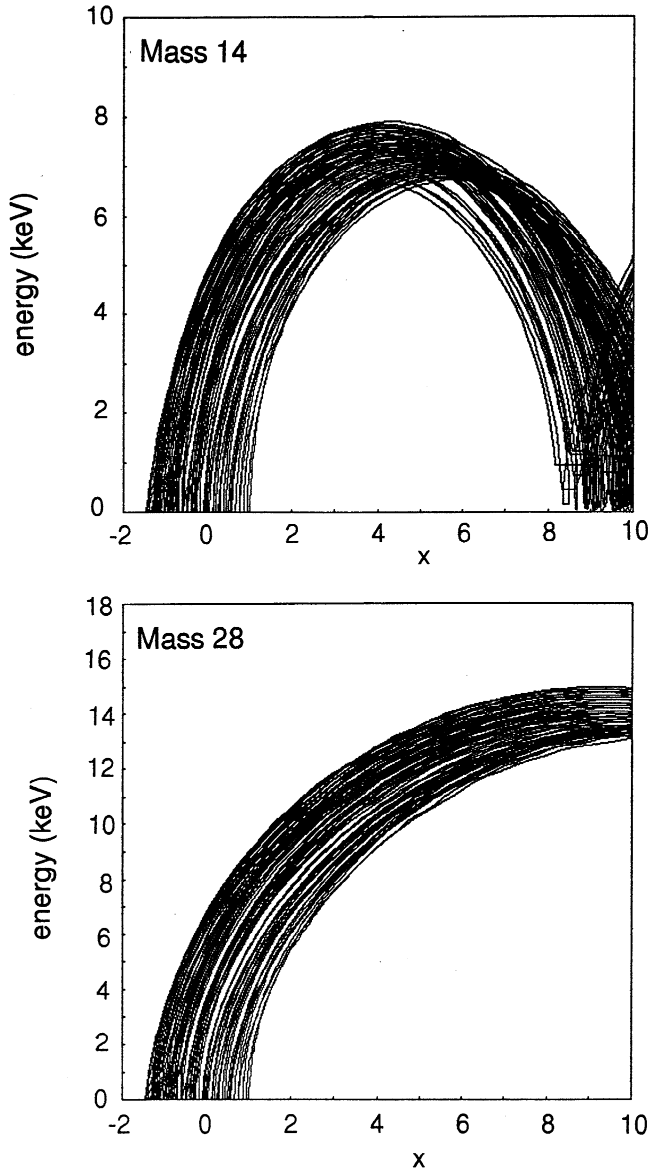

Figure 3. Energies of the pickup ions in Figure 2 as a function of position along the wake (x) axis. (top) mass 14 ions, (bottom) mass 28 ions.

The trajectories in Figure 2 suggest that a spacecraft ion spectrometer flying through the Titan wake at fairly distant locations could detect a sequence of ion beams of different masses and fluxes representative of the Titan upper atmosphere. The flux in each beam would reflect both the density of the neutral parent constituent and the ionization rate. The energy response of the instrument(s) that would be required for these two "species" is indicated by Figure 3, where the energies of the mass 14 and mass 28 ions are shown as a function of position along the wake axis (x). The Cassini mission includes both an ion-neutral mass spectrometer and a more energetic plasma spectrometer that together cover the energy range from a few eV to several tens of keV within which these pickup ions fall. Note that the ability to distinguish between the beams of different species would depend on the distance as well as the orientation of the flyby. The heaviest ions can appear well outside (~9 R_t for mass 28) of the orbit of Titan near the magnetic equatorial plane. The only circumstances under which this ion wake mass dispersion should not be seen are (1) if Titan's plasma environment is highly perturbed so that the wake particles are rapidly scattered, (2) if the primary ion source is deep in the wake-side of Titan, where the plasma and field environment is grossly affected by Titan's presence, (3) if plasma instabilities disrupt the cycloidal motion of the pickup ions close to Titan, or (4) if Titan is in the magnetosheath or solar wind where the ambient magnetic field orientation and magnitude are highly variable.

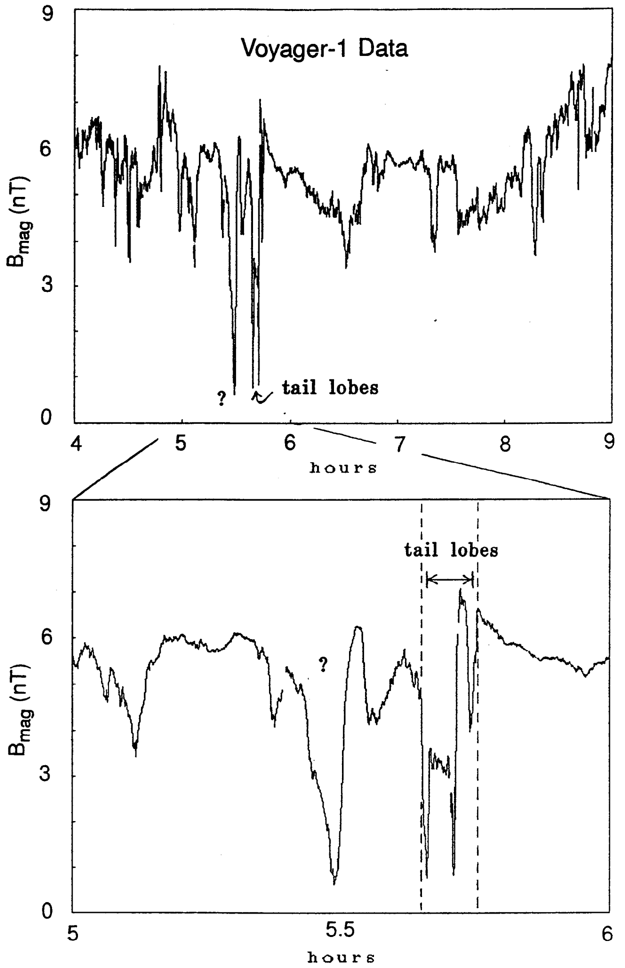

Figure 4. Magnetic field magnitude measured on Voyager 1 around the time of the Titan flyby [*Ness et al.*, 1982]. The bottom lower panel expands the hour around closest approach. The question mark identifies the feature of interest here.

Possible Evidence from Voyager 1

When Voyager 1 flew by Titan it observed a number of asymmetrically located signatures suggestive of ion pickup effects in its wake. These included the detection of possible mass 28 ions and electron density and plasma wave enhancements that were larger on the outside flank of the flow wake [e.g., *Hartle et al.,* 1982; *Gurnett et al.,* 1982]. One particularly notable feature that was not explained was a large magnetic perturbation comparable in magnitude to the wake signature, but displaced a distance outward from the wake. This feature is shown in time series of the field data (obtained by the experiment of *Ness et al.*, [1982]) in Figure 4. The field magnitude is shown because the perturbation is visible primarily in the direction of the ambient field. The location of this feature and some of the other signatures relative to Titan during the Voyager flyby are illustrated in Figure 5a. Figure 5b suggests that the placement of this feature may coincide with the picked-up ion beam(s). Strictly speaking, to determine whether the pickup ions could produce this feature, one would have to construct a global hybrid simulation of the plasma interaction similar to that done for Venus or Mars by *Moore et al.* [1991] or *Brecht and Ferrante* [1991]. Such models allow kinetic treatment of the ions together with the self-consistent effects of the electrons. However, while this is a major project, some insights can be gained using a considerably less ambitious approach to estimate the possible current and related field perturbation due to the pickup ions.

If one assumes that there is a neutralizing electron population that is corotating and that the background magnetospheric ion current is already taken into account by using an observed magnetospheric field that is modified by the ring current, the pickup ion current can be approximated by its contribution because of gyration at the corotation speed. (Since pickup ions in a perpendicular field and flow geometry execute a motion that is a combination of gyration at the corotation speed plus drift of the gyrocenter at the corotation speed, this is equivalent to assuming that the current due to the latter is cancelled by the corotating electron background.) The current due to gyration occupies the space filled by the ion trajectories. Here the "pickup current" in that space is approximated by the (hemispherical) volume-integrated ion production rate above the photochemical boundary at ~1800 km (derived from Figure 1), spread over the cross section of the ion "beam" with a concentration described by a Gaussian with half width 0.5 R_t.

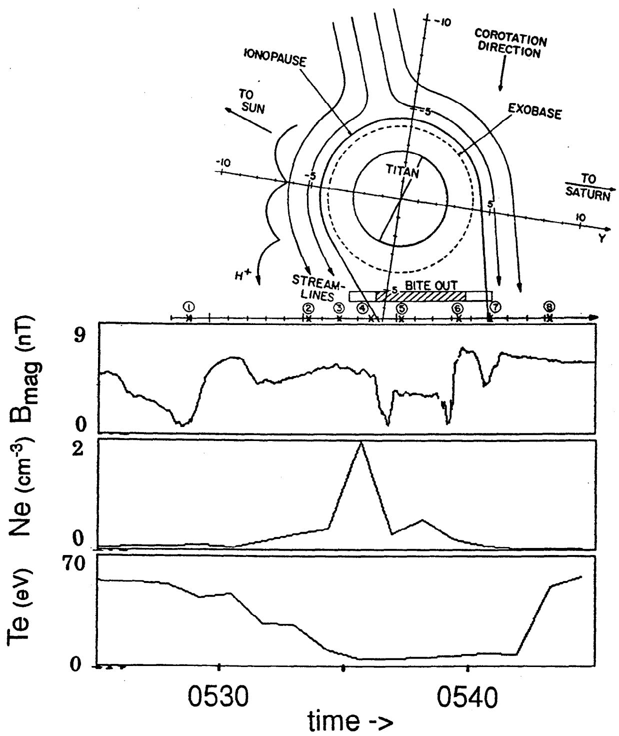

Figure 5. a. Composite showing several perturbations measured in the plasma during the Titan flyby, including the magnetic field, relative to the location of Titan and the detected (aberrated) flow wake. B_{mag} is the magnetic field magnitude, N_e is the electron density, and T_e is the electron temperature (adapted from *Hartle et al.* [1982]).

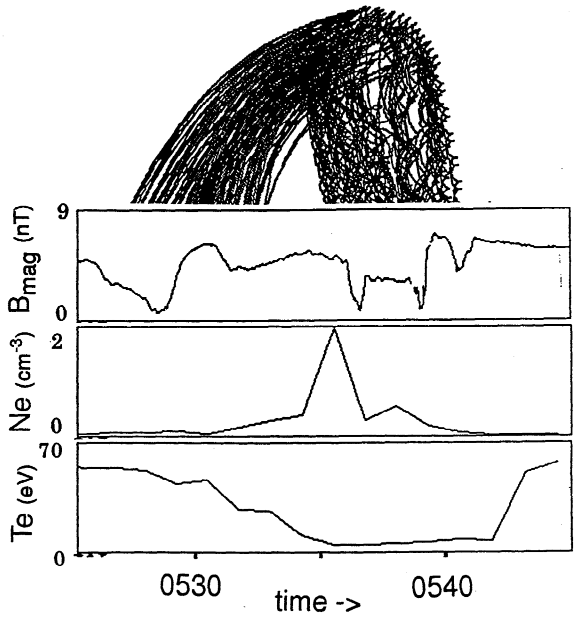

Figure 5. b. Composite similar in layout to Figure 5a, but showing the positions of the observed features relative to the calculated pickup ion trajectories in Figure 2.

The magnetic perturbation produced by this current can be calculated using the Biot Savart law in integral form:

$$\vec{\mathbf{B}} = \mu_0 \int \vec{\mathbf{J}} \times \vec{\mathbf{a}}_r / 4\pi r^2 d(vol) \qquad (1)$$

where $\vec{\mathbf{J}}$ is the current density in coulombs $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ (or amperes per cubic meter), r is the distance from a given volume element ***d(vol)*** to the point of measurement (and $\mathbf{a}_r$ is its unit vector direction), and μ_0 is the standard permeability constant.

In this case it is appropriate to carry out a numerical integration over the volume of the Titan ion wake in the vicinity of the Voyager 1 flyby at about 2 R_t downstream. For this purpose, we constructed a Cartesian grid of cell dimensions $(0.1\ R_t)^3$, filling a cube 20 R_t on each side, with Titan at the center of the "upstream" face. The $+x$ axis defines the corotation wake and the 5 nT background B field is along $-z$, while the y axis completes the orthogonal set. Figure 6 shows the geometry of the model and Figure 7 shows some results. The magnetic field "time series" in Figure 7 were obtained by stepping the integration reference point across the computational grid along paths of constant x (perpendicular to the wake axis) in the Titan equatorial plane. Each dashed line represents one x distance starting at 2 R_t and proceeding tailward by 1 R_t increments. The resemblance of the perturbed field along the $x = 2$ path to the Voyager 1 measurements suggests that the approximations made here may be valid, at least in the vicinity of the 1980 flyby. Note that this simulation does not include the physics that produces the draped "induced magnetotail" of Titan within the corotation wake or any effects of mass loading by the ionospheric ions. Since the Titan magnetotail seems so well confined to the plasma flow wake in the Voyager 1 observations and the trajectories of the heavy pickup ions tend to avoid this region, its neglect is probably not a major concern here. However, significant plasma deceleration in the ramside pickup region could markedly reduce the

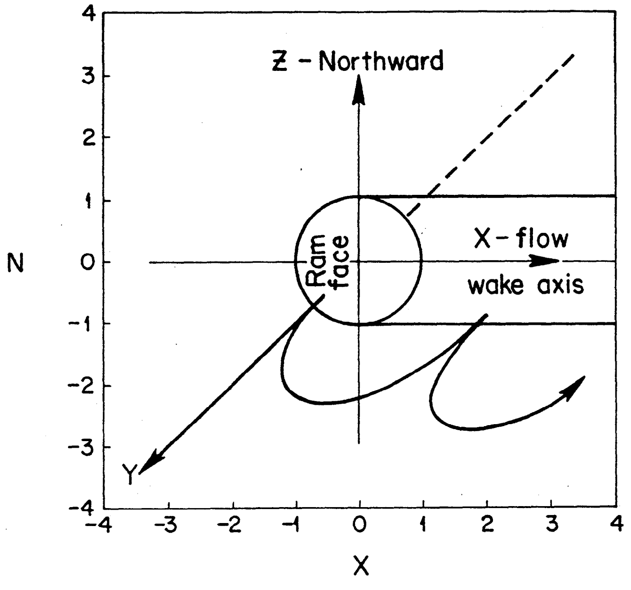

Figure 6. Titan-wake coordinate system used in the pickup ion current and field calculation described here.

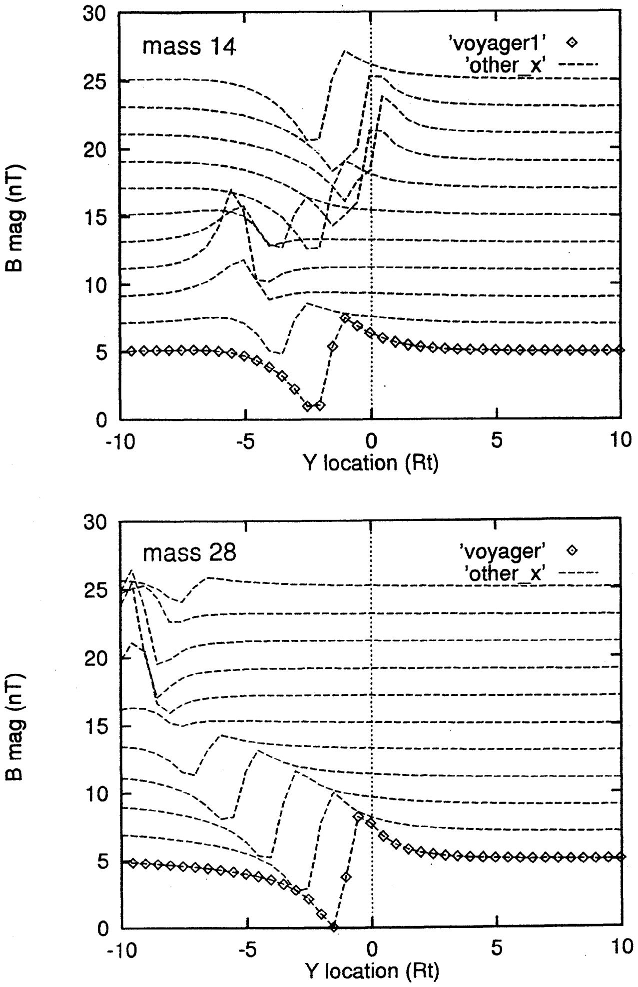

Figure 7. Calculated magnetic fields for comparison with the observed field perturbation during the Voyager flyby. These include only the ambient and pickup ion related fields, and not the draped induced tail field which was neglected in the present simplified model. (top) Mass 14 ions and (bottom) Mass 28 ions. The $x = 2R_t$ simulated time series is marked with symbols and labeled "Voyager 1." Each consecutive time series is displaced vertically by 2 nT for clarity, and corresponds to "trajectories" displaced by intervals of 1 R_t downstream.

pickup ions' gyrovelocities. The positive comparison of the results obtained here with the data suggest that this does not occur, at least for a significant part of the pickup ion population.

It is worth noting that in this "lossless" model, the pickup ion current or particle flux is determined solely by the integrated ion production rate and the spatial spread of the ion beam. It is not dependent on the background flow velocity, although the ions' velocities (or energies) and thus gyroradii are. The pickup ion density, on the other hand, is constrained by the pickup velocity since the flux of ions through the ion beam must match the production rate. For an ion beam cross section comparable to the Titan cross section such as used here, the pickup ion flux is of the order of 10^{11} m^{-2} s^{-1} (compared to the distributed heavy ion background flux of ~20% of this value deduced by *Richardson* [1995] from Voyager 1 observations), while the associated current density is about 10^{-11} A m^{-3}.

Concluding Remarks

The encouraging similarity of the Voyager 1 magnetic field data obtained outside of Titan's corotation wake to the signatures predicted here for the effect of the newly picked-up ions supports the picture of the ion wake structure illustrated in Figure 2. This natural mass spectrometer can in principle be used to "remotely sense" the uppermost atmosphere and ionosphere on the Cassini Orbiter. The Titan pickup ions and their associated magnetic field perturbations are expected to be present at considerable distances outside of Titan's orbit, making advance planning for their observation highly desirable.

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J. G. Luhmann, Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450. (email: jgluhman@sunspot.ssl.berkeley.edu)

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