3-D global MHD model prediction for the first close flyby of Titan by Cassini

Ying-Juan Ma,[1] Andrew F. Nagy,[1] Thomas E. Cravens,[2] Igor V. Sokolov,[1] John Clark,[2] and Kenneth C. Hansen[1]

Received 6 August 2004; revised 28 September 2004; accepted 15 October 2004; published 17 November 2004.

[1] The global features of the interaction between Saturn's magnetospheric plasma flow and Titan's atmosphere/ionosphere are simulated by using a 3-D, multi-species, high spatial resolution, global MHD model. Our model uses a spherical grid structure leading to very good (~36 km) altitude resolution in the ionospheric region of Titan. The model also provides good resolution and meaningful results in the upstream and wake regions. Titan's atmosphere and ionosphere are approximated by 10 neutral and 7 ion species. Calculations, which make predictions for the anticipated results to be obtained by the Cassini spacecraft during its first close flyby (TA) of Titan, are presented. *INDEX TERMS:* 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 2732 Magnetospheric Physics: Magnetosphere interactions with satellites and rings; 2753 Magnetospheric Physics: Numerical modeling. **Citation:** Ma, Y.-J., A. F. Nagy, T. E. Cravens, I. V. Sokolov, J. Clark, and K. C. Hansen (2004), 3-D global MHD model prediction for the first close flyby of Titan by Cassini, *Geophys. Res. Lett.*, *31*, L22803, doi:10.1029/2004GL021215.

1. Introduction

[2] Titan is a unique satellite in the solar system with a dense atmosphere, consisting mainly of molecular nitrogen. Titan's orbit is inside the Saturnian magnetosphere most of the time, however under certain circumstances it may be inside Saturn's magnetosheath region or even in the solar wind. When Titan is inside the magnetosphere of Saturn, the impinging corotating plasma flow is usually subsonic and superalfvenic. Voyager observations established that Titan does not possess an appreciable intrinsic magnetic field and that it has a well developed induced bipolar magnetic tail [*Ness et al.*, 1982]. The interaction of Titan with Saturn's magnetospheric plasma flow involves its atmosphere/ionosphere system. Solar extreme ultraviolet radiation and photoelectron impact ionization are believed to be the major ionization sources for Titan's ionosphere; magnetospheric electron impact ionization contributes significantly to the formation of the ramside ionosphere [*Keller et al.*, 1992; *Nagy and Cravens*, 1998].

[3] Despite the limited relevant data base, a variety of models have been developed for Titan. These include complex 1-D models such as *Fox and Yelle* [1997] and *Cravens et al.* [2004], a 2-D 3-species MHD model by *Cravens et al.* [1998], some 3-D single species or multi-species MHD models [*Ledvina and Cravens*, 1998; *Kabin et al.*, 1999, 2000; *Nagy et al.*, 2001] and a hybrid model by *Brecht et al.* [2000]. These models have greatly improved our understanding of Titan's ionosphere and upper atmosphere as well as the magnetospheric interaction processes. The main difference between our new model and the ones referenced above is that by using a spherical coordinate system, which provides very good radial resolution, we were able to incorporate a realistic ionosphere into the model, which has not been done before. The successful orbit insertion of the Cassini spacecraft and the associated anticipation of significant new results are fueling new interest in this area. In this paper we present results of model calculations that we obtained appropriate for the first close flyby of Titan by Cassini, later this year.

2. Model

[4] The 3-D, multi-species, global ideal MHD model we have used for these calculations is similar to our recent Mars model [*Ma et al.*, 2004] and is described in some detail in that paper. The major difference is that we use seven continuity equations to track the mass densities of the seven "ion species" that we use to approximate the complicated ion chemistry of Titan. These ion species which we adopted for our simplified model are listed in Table 1. *Keller et al.* [1998] have developed a full one dimensional chemical equilibrium model, with a "full" set of 51 ions; this model was further improved/modified by *Cravens et al.* [2004] and J. Clark et al. (Ionospheric predictions for the Cassini Orbiter encounter with Titan, manuscript in preparation, 2004, hereinafter referred to as Clark et al., manuscript in preparation, 2004). Details of the individual production and loss rates are presented in these papers [*Keller et al.*, 1998; *Cravens et al.*, 2004; Clark et al., manuscript in preparation, 2004]. We used their model as a guide to simplify our chemistry scheme down to these seven ion species. They calculated the ionization rates of each of the 51 species as a function of solar zenith angles (SZA), assuming photoionzation and photoelectron impact ionization. We combined, as appropriate, these production rates to obtain the needed values for the primary ions L^+, M^+ and $H1^+$. Next we arrived at approximate/averaged reaction and charge exchange rates, from the individual values, and used them in our simplified scheme. We selected and used the following ten most important neutral species: N_2, CH_4, L(H&H_2), C_2H_2, C_2H_4, C_2H_6, C_3H_4, C_4H_2, HCN and HC_3N {note that we combined atomic and molecular hydrogen into a single

---

[1] Space Physics Research Laboratory, University of Michigan, Ann Arbor, Michigan, USA.

[2] Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas, USA.

0094-8276/04/2004GL021215

Table 1. Species and Group of Ion Species Used in Current Titan Model

No.	Name	Components	Mass (amu)	Mass Range (amu)
1	L^+	H^+, H_2^+, H_3^+	1	1–3
2	M^+	CH_5^+, N^+, CH_4^+, CH_3^+, CH_2^+, CH^+, C^+	14	12–17
3	$H1^+$	$C_2H_5^+$	29	29
4	$H2^+$	HCNH+	28	28
5	MHC^+	C_3H^+, $C_3H_2^+$, $C_3H_3^+$, $C_3H_4^+$, $C_3H_5^+$, $C_4H_3^+$, $C_4H_5^+$, . . .	44	37–53
6	HHC^+	$C_5H_3^+$, $C_5H_5^+$, $C_5H_7^+$, $C_5H_9^+$, $C_6H_5^+$, $C_6H_7^+$, $C_7H_5^+$, . . .	70	63–89
7	HNI^+	$C_3H_2N^+$, $C_5H_5N^+$, C_3HN^+	74	51–79

species}. The density distributions of these neutrals are based on the models of *Yung et al.* [1984], *Yung* [1987] and *Keller et al.* [1992]; the densities of the major species (N_2 and methane) are based on the Voyager ultraviolet occultation measurements, while the densities of the hydrocarbon and nitrile species are calculated by using a photochemical model. Given the limited information available, we assumed in our calculations that the neutral densities do not change with local time or latitude. The electron temperatures that we used were based on the calculations of *Gan et al.* [1992].

[5] The reference frame used in the model is set as follows: the X axis is along the corotation direction, the positive Y direction is from Titan to Saturn and the Z axis completes the right handed co-ordinate system. In order to avoid any possible effects due to the assumed outer boundary conditions we use a very large computational domain, given by $-16R_T \leq X \leq 48R_T$, $-32R_T \leq Y, Z \leq 32R_T$. In these Titan calculations the minimum radial grid size is about 36 km. Our inner boundary was at 725 km above the surface and the ion densities were set at their chemical equilibrium values.

3. Simulation Results

[6] The Cassini spacecraft will flyby Titan on October 26, 2004, within a distance of 1200 km above Titan's surface at its closest approach. This flyby is referred to as the TA orbit. We assumed, for our model simulations, that at that time, Titan will be inside Saturn's magnetosphere. To be consistent with actual condition, the subsolar location is taken to be 70°E, 23°S. We used solar cycle minimum conditions to calculate the ionospheric parameters appropriate for the TA orbit. In order to proceed with the calculations, we also must adopt upstream parameters. The best we can do at this time is to use the parameters available from the Voyager 1 flyby of Titan. The number density of L^+ and M^+ are assumed to be 0.1 cm^{-3} and 0.2 cm^{-3} respectively, the other species are assumed to be zero. The plasma temperature is set as $T_p = 2.6$ keV and the plasma velocity is taken to be $u = 120$ km sec^{-1} along the corotation direction. The vector components of the magnetic field were taken to be −1.0, −0.05, −4.99 nT, respectively [*Nagy et al.*, 2001].

[7] Figure 1 shows the calculated velocities in the equatorial and XZ planes. The color plots show the speed of the plasma and the black arrows show the direction of the flow vector in the corresponding plane. The global features are similar to previous 3-D MHD simulation results: The plasma flow gradually slows down along the ram direction and is clearly diverted around Titan. The flow speed increases significantly in the flank regions as the plasma moves past Titan. The velocity in the X-Y plane reaches values as high as 158 km/s, about 30% larger than the undisturbed corotating plasma flow speed. This acceleration is mainly driven by the magnetic tension force. In the equatorial plane, the plasma flow resembles incompressible potential flow in classical fluid dynamics, except that the acceleration is more dramatic. The different flow patterns in the equatorial and vertical planes are caused by the upstream magnetic field direction.

[8] The calculated magnetic fields in the equatorial and X-Z planes are shown in Figure 2. The color plots represent the magnitude of the total magnetic fields and the black arrows indicate the direction of the magnetic field in the corresponding plane. As can be seen in the vertical plane, the magnetic field lines are highly draped in the near Titan region. In the X-Y plane the magnetic field component far from Titan corresponds to that of the Saturn field, which is extremely small; close to Titan the draping results in field components of a few nT. Magnetic field piles up in front of the body as the plasma flow slows down. A current sheet is formed in the wake region, where the magnetic field is the weakest. The current sheet is much broader in the equatorial plane than the vertical plane. The formation of Alfvén characteristics are clearly seen in the vertical plane. Alfvén wings are produced when a conducting source moves

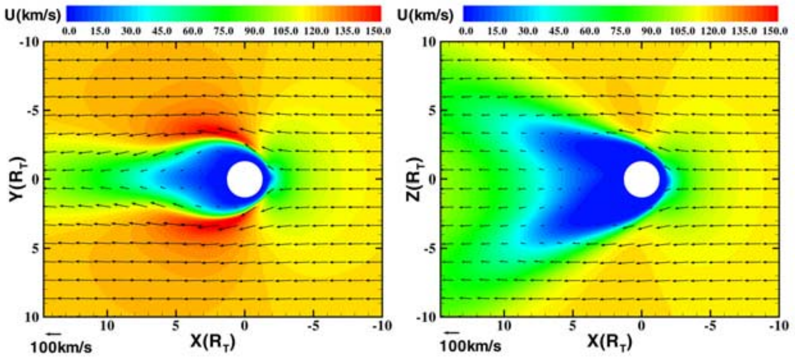

Figure 1. Calculated velocity values in X-Y and X-Z planes. The color plots show the speed of the plasma and the black arrows show the direction of the flow vector in the corresponding planes.

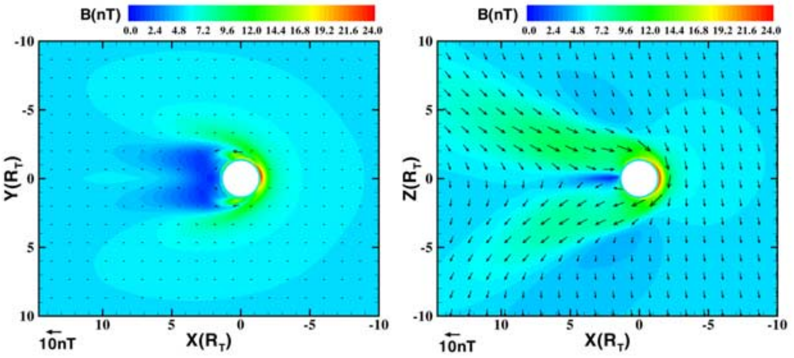

Figure 2. Calculated magnetic field values in X-Y and X-Z planes. The color plots represent the strength of the magnetic field and the black arrows indicate the direction of the magnetic field in the corresponding planes.

uniformly in magnetized plasma [*Neubauer et al.*, 1984]. They are the characteristics of Alfvén waves, which are perturbations along the magnetic field lines. In general, the basic "large scale" results obtained here are consistent with those of the earlier 3-D MHD models of *Ledvina and Cravens* [1998], *Kabin et al.* [1999, 2000] and *Nagy et al.* [2001].

[9] In Figure 3, the calculated ion and electron densities at 60° SZA are plotted along with the results from the Kansas chemical equilibrium model, for comparison. The agreement below about 1400 km is quite good considering we are using a "reduced" chemistry scheme; the significant separation between the results starting near 1400 km is an indication of the altitude where transport becomes important. However, we should note that the altitude region where chemical equilibrium conditions dominate also depend on the ram angle, as was established by our model calculations.

[10] The predictions of Cassini TA flyby are presented in Figure 4. The figure shows what our model predicts would be seen by the relevant Cassini instruments during an interval of about an hour, centered on closest approach. As can be seen from the upper panel, the TA trajectory is located above the equatorial plane and thus the spacecraft does not cross the center of the current sheet. An induced magnetic tail could be detected along the trajectory. The maximum magnetic field magnitude to be encountered is estimated to be about 15.3 nT. Near the closest approach, the maximum electron density is about 3.5×10^3 cm^{-3}, and the heavy species (H1$^+$ and H2$^+$) are dominant near the peak region while the density of the light species is negligibly small.

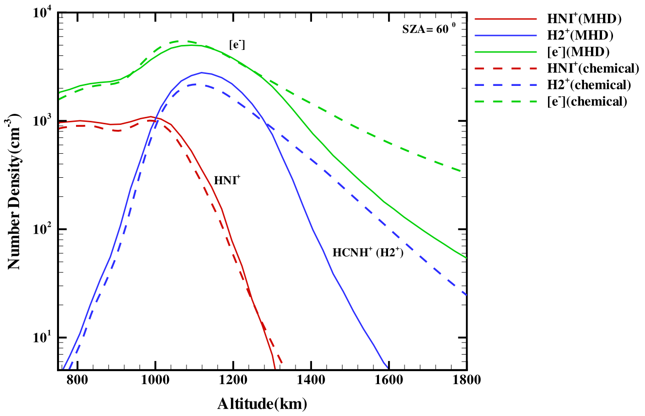

Figure 3. Densities calculated by the 3-D, MHD model along 60° solar zenith angle, compared with the results from the Kansas, one-dimensional, comprehensive chemical equilibrium model.

4. Conclusions

[11] Our multi-species global MHD model allows us to make predictions on the plasma parameters to be measured by the relevant instruments carried by the Cassini space-

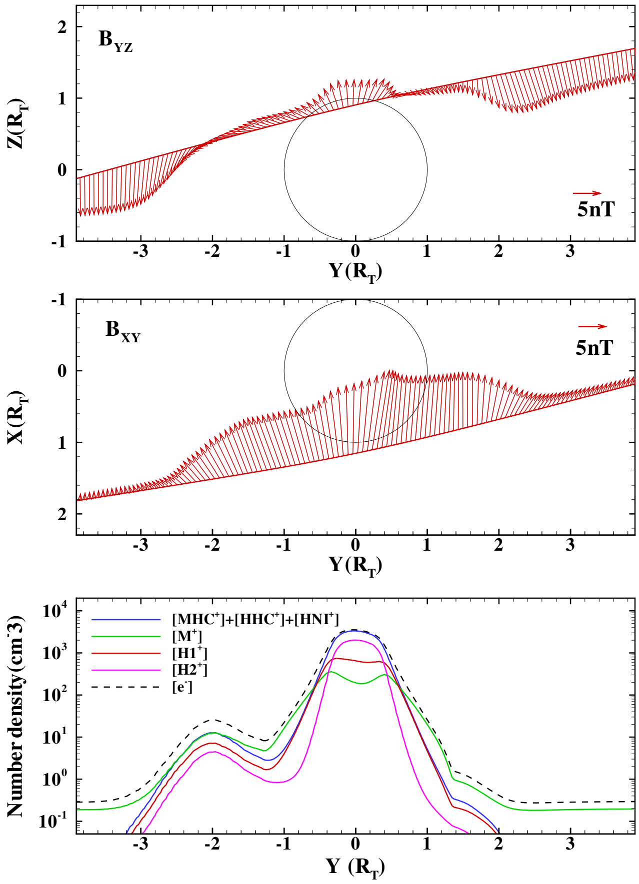

Figure 4. Prediction of magnetic field and ion density along the Cassini TA trajectory near closest approach.

craft. Comparisons between the actual measured values and model predictions allow us to check our current knowledge and make appropriate changes as necessary. This in turn leads to improved understanding of the ionospheric and plasma interaction processes dominating in the environment of Titan.

[12] We did check our model results against the meager data base available from the Voyager 1 flyby of Titan [*Neubauer et al.*, 1984; *Ness et al.*, 1982]. The agreement is reasonably good, but we expect much better and more comprehensive data from the numerous planned flyby of Titan by Cassini and thus look forward to a new era of understanding of Titan's plasma environment.

[13] **Acknowledgment.** The work described here was carried out at the University of Michigan under NASA Grants NAG5-13332 and JPL#961176 and NAG5-11038 at the University of Kansas.

References

Brecht, S. H., J. G. Luhmann, and D. J. Larson (2000), Simulation of the Saturnian magnetospheric interaction with Titan, *J. Geophys. Res.*, *105*, 13,119.

Cravens, T. E., C. J. Lindgren, and S. A. Ledvina (1998), A two-dimensional multifluid MHD model of Titan's plasma environment, *Planet. Space Sci.*, *46*, 1193.

Cravens, T. E., et al. (2004), The ionosphere of Titan: An updated theoretical model, *Adv. Space Res.*, *33*, 212.

Fox, J. L., and R. V. Yelle (1997), Hydrocarbon ions in the ionosphere of Titan, *Geophys. Res. Lett.*, *24*, 2179.

Gan, L., C. N. Keller, and T. E. Cravens (1992), Electrons in the ionosphere of Titan, *J. Geophys. Res.*, *97*, 12,136.

Kabin, K., T. I. Gombosi, D. L. DeZeeuw, K. G. Powell, and P. L. Israelevich (1999), Interaction of the Saturnian magnetosphere with Titan, *J. Geophys. Res.*, *104*, 2451.

Kabin, K., P. L. Israelevich, A. I. Ershkovich, F. M. Neubauer, T. I. Gombosi, D. L. DeZeeuw, and K. G. Powell (2000), Titan's magnetic wake: Atmospheric or magnetospheric interaction, *J. Geophys. Res.*, *105*, 10,761.

Keller, C. N., T. E. Cravens, and L. Gan (1992), A model of the ionosphere of Titan, *J. Geophys. Res.*, *97*, 12,117.

Keller, C. N., V. G. Anacich, and T. E. Cravens (1998), Model of Titan's ionosphere with detailed hydrocarbon ion chemistry, *Planet. Space Sci.*, *46*, 1157.

Ledvina, S. A., and T. E. Cravens (1998), A three-dimensional MHD model of plasma flow around Titan, *Planet. Space Sci.*, *46*, 1175.

Ma, Y., A. F. Nagy, I. V. Sokolov, and K. C. Hansen (2004), Three-dimensional, multispecies, high spatial resolution MHD studies of the solar wind interaction with Mars, *J. Geophys. Res.*, *109*, A07211, doi:10.1029/2003JA010367.

Nagy, A. F., and T. E. Cravens (1998), Titan's ionosphere: A review, *Planet. Space Sci.*, *46*, 1149.

Nagy, A. F., Y. Liu, K. C. Hansen, K. Kabin, T. I. Gombosi, M. R. Combi, D. L. DeZeeuw, K. G. Powell, and A. J. Kliore (2001), The interaction between the magnetosphere of Saturn and Titan's ionosphere, *J. Geophys. Res.*, *106*, 6151.

Ness, N. F., M. H. Acuna, K. W. Behannon, and F. M. Neubauer (1982), The induced magnetosphere of Titan, *J. Geophys. Res.*, *87*, 1369.

Neubauer, F. M., D. A. Gurnett, J. D. Scudder, and R. A. Hartle (1984), Titan's magnetospheric interaction, in *Saturn*, edited by T. Gehrels and M. Shapley Matthews, p. 760, Univ. of Arizona Press, Tucson.

Yung, Y. L. (1987), An update of nitrile photochemistry on Titan, *Icarus*, *72*, 468.

Yung, Y. L., M. Allen, and J. P. Pinto (1984), Photochemistry of the atmosphere of Titan: Comparison between model and observations, *Astrophys. J. Suppl.*, *55*, 465.

K. C. Hansen, Y.-J. Ma, A. F. Nagy, and I. V. Sokolov, Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109, USA. (yingjuan@umich.edu)

J. Clark and T. E. Cravens, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA.