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Studies of the Gas Tori of Titan and Triton

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TABLE OF CONTENTS

I. INTRODUCTION

The general objective of this project is to advance our theoretical understanding of gas tori for the outer planet satellites and hence to enhance our ability to interpret observational data and to make available key concepts or quantitative results that are relevant to a number of other related theoretical studies. These studies include the aeronomy and photo- and ion chemistry of satellite atmospheres and their predicted gas loss rates, the evolution and distributions of gases in the larger planetary environment, and the ion loading and other impacts of these gases on the composition, structure, and properties of the planetary magnetospheres. Important objectives of this project are to explore for the satellites Titan and Triton the effects of two new mechanisms that we have very recently discovered (Smyth and Marconi 1993) to operate on gas tori in the outer planet satellite systems. These two mechanisms can dramatically alter the current picture that has been widely adopted for the structure and evolution of long-lived gas tori (i.e., lifetime long enough to achieve approximate azimuthal symmetry about the planet) and, in particular, have profound consequences on the interpretation of Voyager data for both neutral and ionized species in the circumplanetary environments of Saturn and Neptune. Due, however, to the substantially reduced budget support available for this project, the primary emphasis of the research will be focused on the Titan component, with a limited (but still important) effort to be expended on the Triton component.

For the Saturn system, comparable amounts of thermal H and H_2 and a much smaller amount of nonthermal N are thought to escape Titan and form gas tori. These tori are thought to be essentially collisionless because the lifetime loss processes of these gases in the moderate Saturn magnetosphere, although slow, are sufficiently rapid to avert collisional conditions. For the atomic hydrogen torus, the perturbation of solar radiation pressure experienced by H atoms as they resonance scatter Lyman-α photons --- the first new mechanism --- was shown by Smyth and Marconi (1993) to be operative and to destroy the normally assumed cylindrical symmetry of the torus produced by the 1/r central potential of a planet. This new mechanism causes H atom orbits to evolve inward as their eccentricities increase, and a significant fraction of these atoms are lost from the torus (having a preferred orientation of their perigee-axes) by colliding with the planet near its dusk side before they are otherwise lost through lifetime processes. This time evolution for a typical H atom lost from Titan is shown in Figure 1. Solar radiation pressure thus provides a natural mechanism for understanding the asymmetric distribution of hydrogen about Saturn recently reported by Shemansky and Hall (1992). This new understanding will subsequently allow the current question of the consistency of this atomic hydrogen distribution with the composition and properties of the inner magnetospheric plasma and the inner icy satellite tori to be addressed more clearly. In contrast to atomic hydrogen, H_2 and N will escape Titan and form approximately azimuthally symmetric tori about Saturn (i.e., the traditionally adopted torus picture) since, for both species, solar radiation pressure is not important and the loss by lifetime processes is sufficiently long to achieve symmetry. The study of the spatial nature and the study of the physical consequences of all three of these gas tori of Titan are undertaken in this project in a straightforward three-year program summarized in Table 1.

For the Neptune system, comparable amounts of H and H_2 and N are thought to escape thermally from Triton and form gas tori. The lifetimes of these three gases in the magnetosphere of Neptune are, however, very long and are comparable to their photo-lifetimes because of the low plasma density and the small fraction of time that the tori spend in the more dense regions of the magnetosphere which executes complex motion about the planet. Because of these long lifetimes, the density of each torus will be collisional, and the neutral-neutral collision time will be shorter than all other time scales except for the typical Kepler orbit period of the atom or molecule (see Table 1 in Smyth and Marconi 1993). The collisional nature of the three gases will cause the multi-species gas torus to dynamically evolve in an inherently nonlinear manner that will depend upon the 1/r nature of the potential of the planet. This collisional evolution will cause the gas torus to expand both inwardly (leading to inward gas loss by collision with the planet's atmosphere) and outwardly (leading to volume dilution and outward gas loss by escape from the planet). This expansion mechanism, the second new mechanism noted above, is a non-linear effect that has been known for two decades in the field of solar system and ring formation but has been previously overlooked as important until now for the field of collisional gas tori about planets (Smyth and Marconi 1993). The final structure and density of the gas torus of Triton are particularly important in understanding the plasma sources recently identified in the analysis of the Voyager PLS data for the Neptune magnetosphere. This fascinating new expansion mechanism for the multi-species collisional gas torus of Triton provides a challenging dynamical evolution problem. Due to the reduced budget support available for this project, the solution of this problem to be undertaken in this project for Triton will be diminished in scope from that outlined in the original three-year plan summarized in Table 1. The Triton component will be initiated when it is clear that significant progress will have been achieved for the Titan component.

II. STUDIES FOR THE TITAN TORUS

2.1 Model Development

The model for the distribution of hydrogen in the Saturn system, which calculates the orbits according to the perturbation theory described in Smyth and Marconi (1993), has been augmented by the addition of a continuous source of atoms rather than a time pulse of atoms. In principle, this source can now have any time dependence desired. Instead of simply counting particles which are lost to the central planet by collisional encounters, the program has been modified in the first project year to calculate the two-dimensional column density and the Lyman-α brightness on a viewing plane that is produced by the collection of all the H atom trajectories. A central source of atoms (i.e., from the central planet) has been also added but is not yet fully functional. The central source may emit atoms with a given velocity distribution and surface distribution (currently, Maxwellian and hemispherical, respectively), and its contribution to the column density determined.

Examples of some preliminary results are presented in Figures 2 and 3. In both Figures, hydrogen atoms are emitted with a 189 K Maxwellian from Titan, and the initial effect on the atom energy loss due to the gravitational attraction of Titan is included. The subsequent orbital motion of the atoms is determined by the gravitational field of Saturn (including the non-spherical J_2 term) and by a constant radiation acceleration of 6.9×10^{-3} cm sec^{-2}. The hydrogen atoms are also lost from the circumplanetary environment by reactions with electrons and ions in Saturn's Magnetosphere according to the model described in Smyth and Marconi (1993).

2.2 Preliminary Model Calculations

Figure 2 shows the calculated history of the number of atoms per second (in arbitrary units) that crash into the planet during a time interval of 2×10^9 s, which is a little longer than two Saturn orbital periods (1.86×10^9 s) around the Sun. The zero on the time axis corresponds to the beginning of Saturnian Fall (autumnal equinox). After an initial transient lasting about 10^8 s, a periodic behavior is observed with higher collision rates near times of 4.7×10^8 s, 9.3×10^8 s, 14×10^8 s, and 18.7×10^8 s which represent the beginning of fall, spring, fall, and spring respectively through two successive Saturn orbits. In contrast, at the beginning of winter and summer (in between the above times) when the ellipse of Titan's orbit is most open relative to the Sun, the crashing rates are significantly less. The number of atoms in the circumplanetary environment therefore varies with the Saturn season. The smaller high frequency oscillations imposed on the larger oscillations are statistical fluctuations associated with the finite number of orbits (10,000) used in this calculation.

Figure 3 shows the calculated column density at the beginning of winter as viewed above Saturn along a line of sight perpendicular to its ecliptic plane. The column density units are arbitrary, and the dotted line represents the location of Saturn. For this example, 10,000 atom trajectories were also integrated. The Sun is to the right with the horizontal axis being parallel to the Saturn-Sun line and the vertical axis being in the direction of Saturn's motion around the Sun. The distance units are in Saturn radii. The most obvious feature is the accumulation of hydrogen density near the dusk side of Saturn (the upper right hand corner). This concentration of hydrogen gas near the dusk side of Saturn is qualitatively similar to the asymmetrical distribution of hydrogen about Saturn reported by Shemansky and Hall (1992) as observed by the UVS instruments aboard the Voyager spacecrafts during their flybys of the planet. The investigation of these Voyager observations will be the subject of research undertaken in the second project year (see Table 1).

REFERENCES

Shemansky, D. E. and Hall, D. T. (1992) The Distribution of Atomic Hydrogen in the Magnetosphere of Saturn, J. Geophys. Res. 97, 4143-4161.

Smyth, W. H. and Marconi, M. L. (1993) The Nature of the Hydrogen Tori of Titan and Triton, Icarus 101, 18-32.

Table 1

GAS TORI: THREE-YEAR PLAN OF STUDY

Subject	First Year	Second Year	Third Year
1. Titan Gas Tori			
H Torus	Complete model development; compute the density distribution and Lyman-α brightness distribution in the Saturn environment.	Investigate the Voyager UVS Lyman-α observations; evaluate the relative importance of the Titan source and an asymmetric Saturn hydrogen source.	Investigate the consistency of the atomic hydrogen distribution with the composition and properties of the magnetospheric plasma and the inner icy satellite tori.
H_2 and N Tori	-----	Set up the gas tori models for H_2 and N.	Calculate the density of the H_2 and N tori and their ion sources for the planetary magnetosphere.
2. Triton Gas Tori			
H, H_2 and N Tori	Develop a general model for the dynamical evolution of a collisional multi-species gas torus.	Complete development; explore the dynamical evolution for the restricted case of a single-species gas torus for H, H_2 and N individually.	Explore the dynamical evolution for a multi-species gas torus for H, H_2, and N.

FIGURE CAPTIONS

Figure 1. **Time Evolution of a Hydrogen Atom Lost from Titan.** The projection on the satellite plane of the initial orbit of a hydrogen atom lost from Titan is labeled by 1. This typical orbit has a semimajor axis of 22 Saturn radii, an eccentricity of 0.14, an inclination angle of 23° relative to the satellite plane, a right ascension of the ascending node of - 90°, and an argument of perigee of 242°. The time evolution of the hydrogen atom orbit is illustrated by its projected orbit on the satellite plane labeled by 2, 3 and 4 and corresponds, respectively, to times of 3×10^7 s, 5×10^7 s, and 7×10^7 s. The planet is indicated by the circle at the intersection of the two axes in the satellite plane, and the direction of the sun is to the right as indicated by the star symbol. The hydrogen atom collides with the planet near its dusk side in about 10^8 s.

Figure 2. **Time History of H Atoms Colliding with Saturn**. The seasonal time history for the collision rate (in arbitrary units) with Saturn of the H atoms, which initially and continuously escape from Titan and which subsequently move inward due to orbital evolution driven by solar radiation acceleration, is shown for 2×10^9 s, a little more than two orbital periods of the planet about the Sun. See text for discussion.

Figure 3. **Hydrogen Column Density as Viewed from above the Ecliptic plane for Saturn**. The calculated H column density (in arbitrary units) at the beginning of winter, as viewed from above the ecliptic plane for Saturn and produced by the continuously escape of hydrogen from Titan, is shown. See text for discussion.

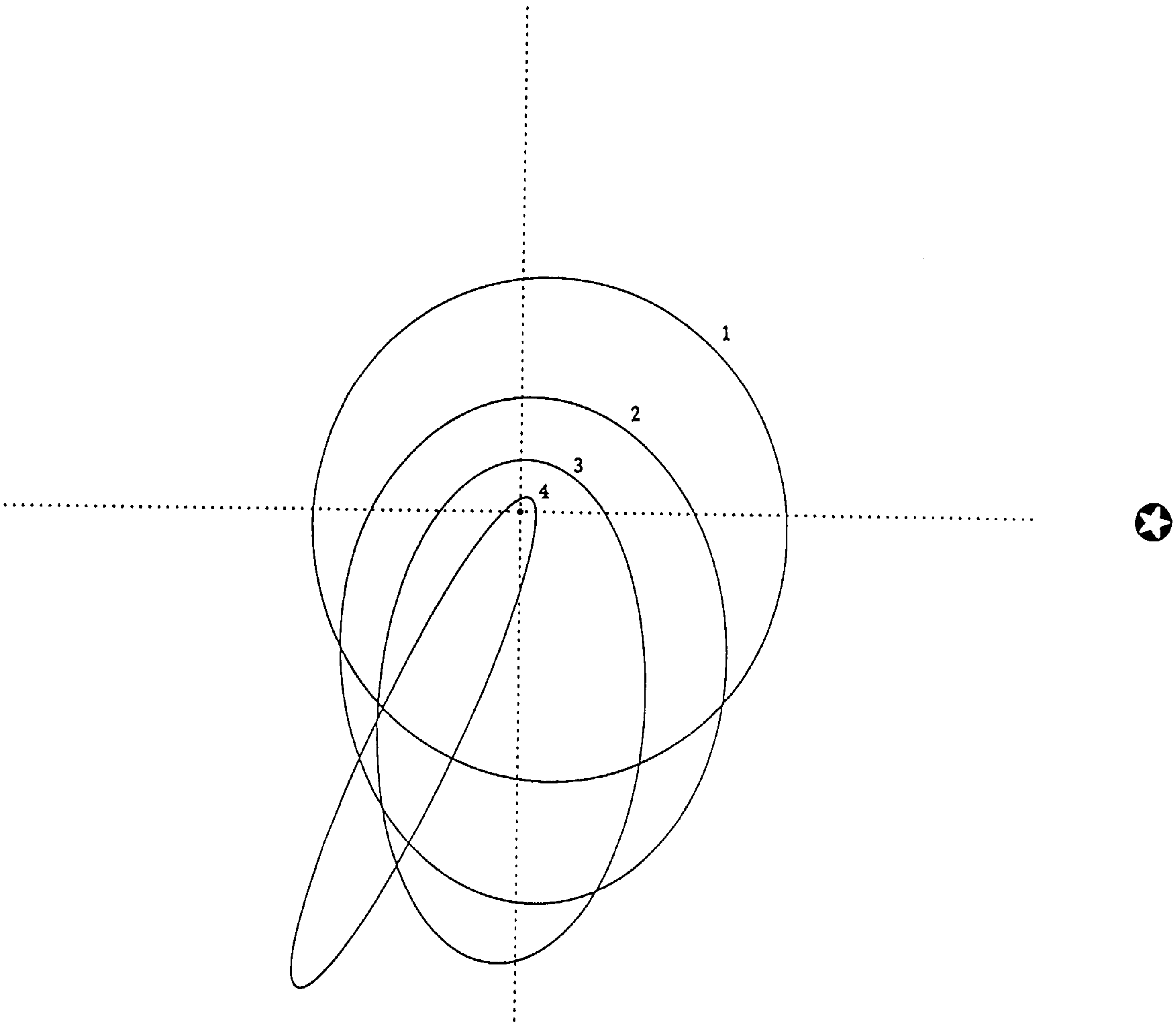

Figure 1

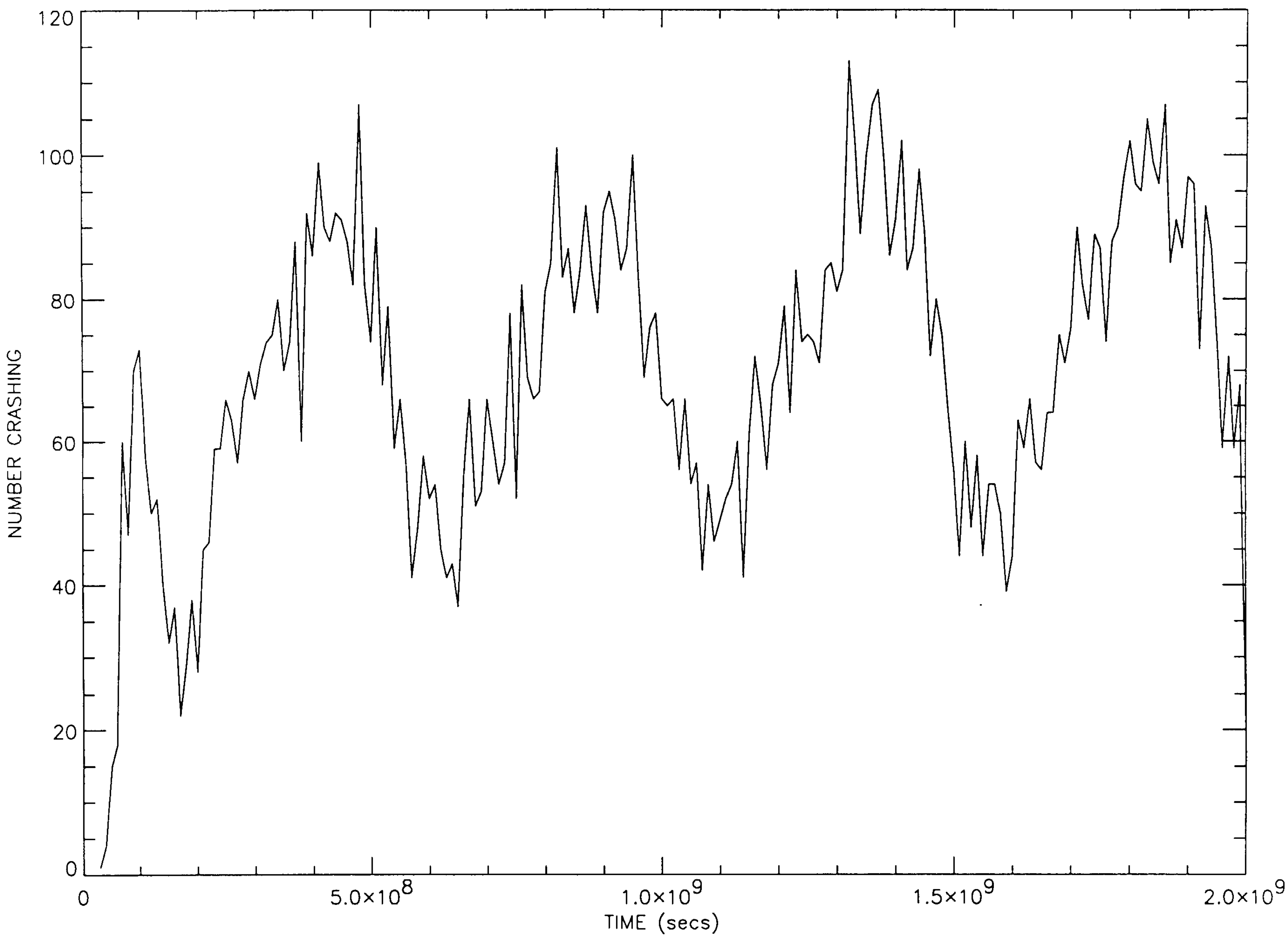
120
100
80
60
40
20
0
NUMBER CRASHING
0
5.0×10^8
1.0×10^9
1.5×10^9
2.0×10^9
TIME (secs)

Figure 2

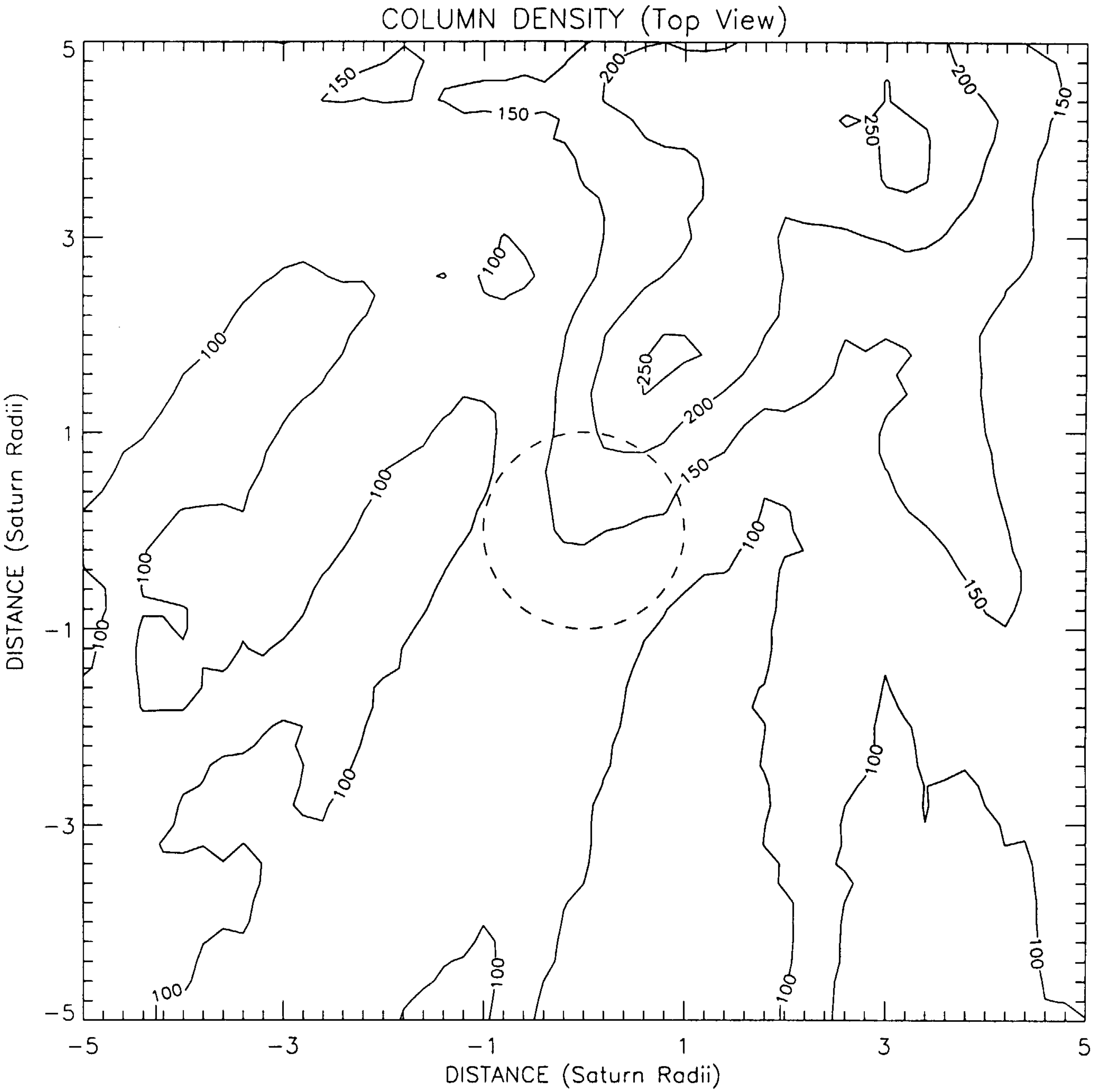
COLUMN DENSITY (Top View)
DISTANCE (Saturn Radii)
DISTANCE (Saturn Radii)
5
3
1
−1
−3
−5
−5
−3
−1
1
3
5
250
250
200
200
150
150
150
150
100

Figure 3

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Progress in the development of the model for the circumplanetary distribution of atomic hydrogen in the Saturn system produced by a Titan source is discussed. Because of the action of solar radiation acceleration and the obliquity of Saturn, the hydrogen distribution is shown to undergo seasonal changes as the planet moves about the Sun. Preliminary model calculations show that for a continuous Titan source, the H distribution is highly asymmetric about the planet and has a density maximum near the dusk side of Saturn, qualitatively similar to the pattern recently deduced by Shemansky and Hall (1992) from observations acquired by the UVS instruments aboard the Voyager spacecrafts. The investigation of these Voyager data will be undertaken in the next project year.

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