

## 2.10 GASEOUS TOROID AROUND SATURN

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### Introduction

It has been suggested (McDonough and Brice 1973a) that Titan's escaping atmosphere could be trapped in the Saturnian System in the form of a toroidal ring or "doughnut". The radius of the toroid would be comparable to Titan's orbit, or about ten times larger than the visible rings. Theoretical analyses of the toroid have been made by McDonough and Brice (1973b), Dennefeld (1973), Tabarié (1973), and Sullivan (1973).

The condition that the majority of escaping atoms or molecules from Titan be unable to escape Saturn's gravitational attraction is that the exospheric thermal velocity be less than or comparable to the orbital speed of Titan,  $V_T$ , or numerically,

$$T_{\text{ex}} \lesssim 1200m \quad (1)$$

where  $m$  is the atomic or molecular weight, and  $T_{\text{ex}}$  is the exospheric temperature in  $^{\circ}\text{K}$ . Thus, if the exospheric temperature is within an order of magnitude of Trafton's (1972a) Titanian exospheric temperature of  $74^{\circ}\text{K}$ , most of the escaping atmosphere will orbit Saturn regardless of its composition.

The possibility of much higher exospheric temperatures has been suggested independently by Gross and Mumma (1973) in which case the temperature might violate Equation 1. Then, while most of the gas might escape Saturn, some fraction of it would still be retained, with the Titanian escape flux still yielding a substantial amount of gas orbiting Saturn. However, the models presented here at the Workshop predict temperatures that easily satisfy Equation 1.

A constraint on the composition and density of a Saturnian toroid is given by the paper of Franklin and Cook (1969). They studied principally the constraint on the amount of sodium vapor surrounding Saturn's visible rings. They derived an upper limit of  $\sim 100$  Na atoms  $\text{cm}^{-3}$  for a gas ring comparable in size to the visible rings, which yields an upper limit  $\sim 10$  times smaller for the proposed toroid. Their paper placed no constraints on the probable constituents of the toroid (H,  $\text{H}_2$ ,  $\text{CH}_4$ , etc.).

### Size of the Toroid

Characteristic inner and outer radii of the toroid,  $r_{\pm}$ , are given, from celestial mechanics, by:

$$\frac{r_{\pm}}{r_T} = \left[ 2 \left( \frac{V_T}{V_T \pm V_{\text{th}}} \right)^2 - 1 \right]^{-1} \quad (2)$$

where  $r_T$  is Titan's orbital radius and  $V_{th}$  is the RMS thermal speed of the particle immediately after escape from Titan. The thickness of the toroid,  $\Delta Z$ , perpendicular to the equatorial plane, is:

$$\Delta Z/r_T \simeq 2 V_{th}/V_T \quad (3)$$

For 70°K hydrogen atoms (or 100°K hydrogen molecules or 280°K methane molecules),  $r_-/r_T$ ,  $r_+/r_T$ , and  $\Delta Z/r_T$  are 0.4, 3, and 0.5, respectively. A schematic top view of this toroid is shown in Figure 2-38.

#### Hydrogen Density in the Toroid

If the average toroid particle survives for a period of time  $T$ , and if we estimate the volume of the toroid to be  $\sim r_T^3$ , then its mean density,  $N_T$ , is:

$$N_T \sim FT/r_T^3 \quad (4)$$

where  $F$  is the atmospheric escape rate from Titan. Trafton (1972a) estimates  $F$  to be from  $2 \times 10^{26}$  to  $4 \times 10^{29}$   $H_2$  molecules  $sec^{-1}$  and Hunten's (1973a) maximum escape flux is slightly smaller than the latter figure. If we take as a characteristic lifetime the ionization lifetime of hydrogen atoms at Saturn's distance,  $T$  is 6 yr and Equation 4 implies densities from  $\sim 10$  to  $\sim 10^4$  molecules  $cm^{-3}$ .

Tabarić (1973) independently estimates, for a series of Titanian model atmospheres, escape fluxes of hydrogen molecules from  $5 \times 10^{27}$  to  $9 \times 10^{32}$  mols  $sec^{-1}$ . The associated atomic hydrogen escape fluxes range from  $8 \times 10^{26}$  to  $10^{27}$  atoms  $sec^{-1}$ . It would appear from these estimates that the density of atomic hydrogen in the toroid is greater than  $10$  atoms  $cm^{-3}$  and would thus be optically thick at Lyman- $\alpha$  wavelengths. However, the above density estimates may need to be lowered because of recapture of the hydrogen by Titan as discussed below.

#### Recycling of Titan's Atmosphere

Particles which escape Titan but not Saturn will orbit in elliptical trajectories that intersect Titan's orbit, unless they are perturbed. Since the particle can orbit Saturn many times, Titan and the particle may happen to pass through the same region at the same time, allowing the particle to be recaptured. The effective area of Titan for recapture of toroid particles may be much larger than Titan's visible area because its exospheric radius may be an order of magnitude larger than the visible radius (Trafton 1972a, Hunten 1973a), due to Titan's weak gravitational field. It is estimated (McDonough and Brice 1973a,b), using a simplified orbital model, that up to  $\sim 98\%$  of 100°K hydrogen molecules could be recaptured in this way, if the radius of the base of Titan's exosphere is of the order  $2.5 \times 10^4$  km. It remains to be investigated whether interparticle collisions, gravitational perturbations, or radiation pressure significantly alter the orbits to hinder this atmospheric recycling phenomenon.

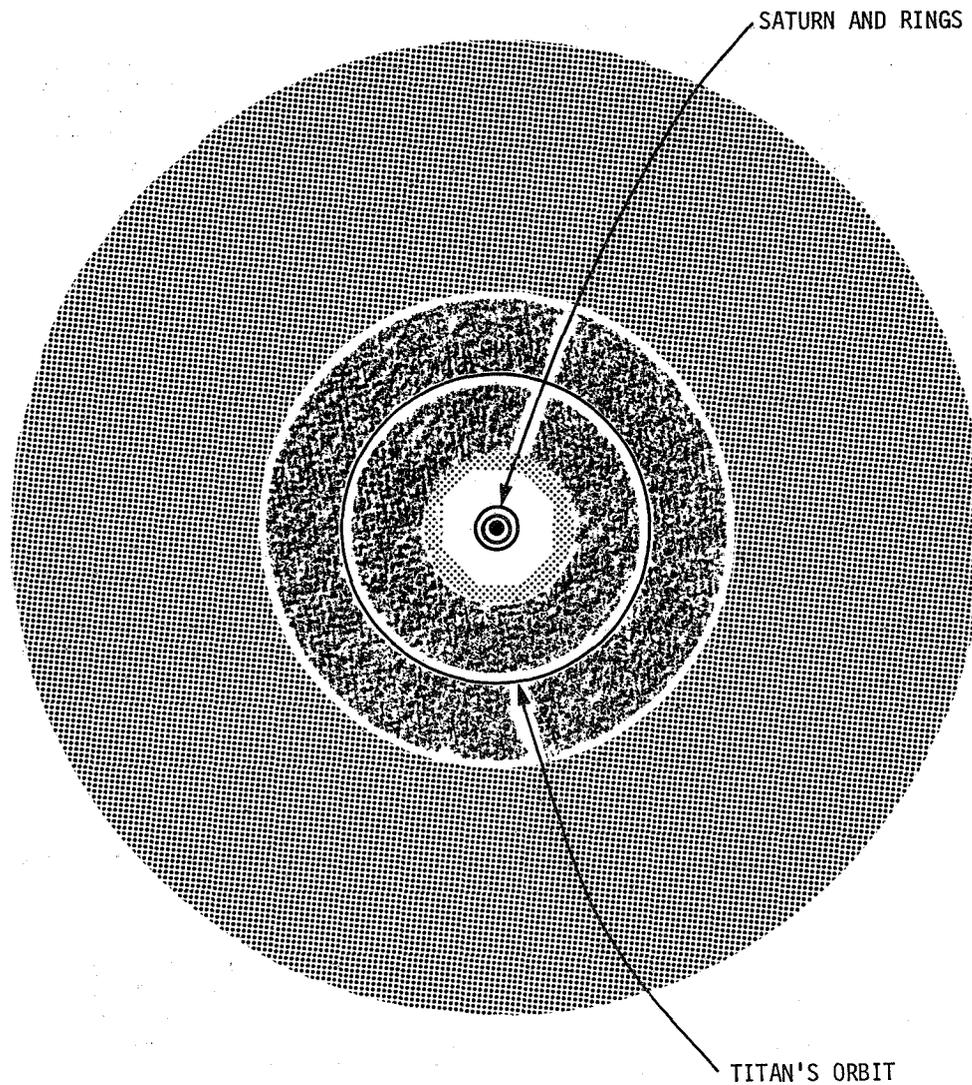


Figure 2-38. The Titan toroid, as viewed from above, is represented by the shaded areas. The boundaries shown are approximate, representing regions of different densities. These boundaries are estimated for  $100^{\circ}\text{K H}_2$ , and are diffuse. Saturn, the visible Rings, Titan's orbit, and the Sun's absolute diameter are shown approximately to scale. After McDonough and Brice (1973). Reprinted from *Icarus*, 20:138, with permission of Academic Press, Inc. Copyright © 1973 by Academic Press, Inc. All rights of reproduction in any form reserved. Printed in Great Britain.

### Effects of a Saturnian Magnetosphere

If Saturn has a magnetosphere similar to Jupiter's, which extends to the vicinity of Titan's orbit, it will protect toroid particles from direct ionization by solar-wind particles, although some ionization by solar-wind particles that penetrate the magnetopause and diffuse to the toroid is possible. Photoionization and photodissociation would probably be important. Furthermore, corotating magnetospheric plasma could ionize the toroid particles. Observation of the toroid density as a function of radius could thus provide information on the presence or absence of a Saturnian magnetosphere.

### Scientific Usefulness of the Toroid

The composition of the toroid would reflect the composition of Titan's atmosphere, and could provide information (possibly even from Earth orbit) on whether the Titanian atmosphere is in a condition of blow off, on whether hydrogen is present in substantial amounts in the atmosphere of Titan, and on the ratio of atomic to molecular hydrogen. If the toroid can be mapped, e.g., by ultraviolet photometry, the Titanian exospheric temperature and net loss rates may be found from Equations 2 through 4. The density of the toroid as a function of radius and azimuth could provide information on day-night asymmetries at Titan, the possible Saturnian magnetosphere, and the rotation rate of Titan.

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Pollack: Can we compare Trafton's and Hunten's escape fluxes? Were they referred to the same level?

Trafton: Mine were shown for both the critical level and the surface; the total escape rate was up to  $5 \times 10^{29}$  molecules/sec.

Hunten: And mine were all referred back to the surface. If we take a typical flux of  $10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$ , the total rate is almost  $10^{29} \text{ sec}^{-1}$ , so we are basically in agreement. However, I remind you that my calculation depends only on the rate of diffusion. If the exosphere temperature is changed, or hydrogen is recycled from the toroid, the structure of the corona changes to maintain the same net loss rate.

Strobel: What is the time required to fill the toroid to equilibrium, if it started out empty?

McDonough: The average atomic-hydrogen lifetime in the toroid is about 150 orbits or 6 years and is determined by the rate of ionization of the hydrogen. The time to fill the toroid would be of this same order, unless recapture is important.

Hunten: Regarding your estimate of up to 98% of the hydrogen being recaptured; if that were to occur, the lower net escape flux will increase the exospheric density, hence, re-establishing the original net escape flux. The flows may be more hydrodynamic than molecular at this point, which could further inhibit your suggested high recapture flux.

Regarding perturbations of the atomic orbits, I calculated some time ago that for a particle density in the toroid of  $10^3$  particles  $\text{cm}^{-3}$ , the mean free path is about equal to the toroidal circumference. I am not sure what this mean free path does to the density distribution but it should randomize the orbits rapidly.

Sagan: Would the toroid have a detectable effect on the solar wind?

McDonough: Yes, it has a depth of one mean free path for charge exchange when the density is  $10^3$   $\text{cm}^{-3}$ . So it will cast a shadow if it is at least that dense.

Pollack: How bright would the toroid be in Lyman- $\alpha$ ?

Blamont: Maybe as much as 500 Rayleighs which is somewhat greater than the 300 Rayleigh diffuse background glow.

McDonough: I think the scattering from the toroid could be distinguished if there were enough spectral resolution to separate the components by their Doppler shifts. An OAO-type spacecraft would be ideal for looking at the toroid, although the field of view and the slits are probably too narrow on the Copernicus spacecraft.

Caldwell: The first OAO did try to detect Lyman- $\alpha$  from Saturn, but as I recall, it did not succeed for several reasons.