IN-91-CR
260654
18P.

JPL Publication 89-37

Neptune's Triton: A Moon Rich in Dry Ice and Carbon?

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August 15, 1989

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(NASA-CR-186293) NEPTUNE'S TRITON: A MOON
RICH IN DRY ICE AND CARBON (JPL) 18 p
CSCL 03B

N90-16675

Unclas
G3/91 0260654

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 89-37

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Neptune's Triton: A Moon Rich in Dry Ice
and Carbon?

5. Report Date
August 15, 1989

6. Performing Organization Code

7. Author(s) A.J.R. Prentice

8. Performing Organization Report No.

9. Performing Organization Name and Address

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

10. Work Unit No.

11. Contract or Grant No.
NAS7-918

13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546

14. Sponsoring Agency Code
BP-889-59-06-53-11

15. Supplementary Notes

16. Abstract

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17. Key Words (Selected by Author(s))

Space Sciences (General)
Astronomy
Voyager Project

18. Distribution Statement

19. Security Classif. (of this report) Unclassified

20. Security Classif. (of this page) Unclassified

21. No. of Pages 11

22. Price

JPL 0184 R 9/83

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This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

The encounter of the spacecraft Voyager 2 with Neptune and its large satellite Triton in August 1989 will provide a crucial test of ideas regarding the origin and chemical composition of the outer solar system. In this pre-encounter publication we quantify the possibility that Triton is a captured moon which, like Pluto and Charon, originally condensed as a major planetesimal within the gas ring that was shed by the contracting protosolar cloud at Neptune's orbit. Ideas of supersonic convective turbulence are used to compute the gas pressure, temperature and rate of catalytic synthesis of CH_4, CO_2 and C(s) within the protosolar cloud, assuming that all C is initially present as CO. The calculations lead to a unique composition for Triton, Pluto, and Charon: each body consists of, by mass, $18\frac{1}{2}\%$ solid CO_2 ice, 4% graphite, $\frac{1}{2}\%$ CH_4 ice, 29% methanated water ice and 48% of anhydrous rock. This mix has a density consistent with that of the Pluto–Charon system and yields a predicted mean density for Triton of 2.20 ± 0.05 g/cm^3, for satellite radius equal to 1,750 km.

FOREWORD

This report was written at the Department of Mathematics, Monash University, Clayton, Victoria 3168, Australia. It was originally submitted for publication to *Nature* (London) on July 10, 1989 [designated manuscript no. P07117].

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The greatest clue to Triton's origin lies in its orbit about Neptune: the orbital plane is inclined $\sim 159^\circ$ relative to Neptune's equator, meaning that Triton actually moves in a retrograde sense about the planet. Such an irregularity argues against Triton being a naturally formed moon of Neptune (N) like the regular satellite systems of Jupiter (J), Saturn (S) and Uranus (U)[6-8]: all of these latter systems orbit the parent body in a prograde sense. Instead, it seems dynamically more likely[1] that Triton was captured from a solar orbit after having first condensed as a major planetesimal within the protosolar cloud. We shall not pursue the capture process in more detail here, beyond pointing out that gas drag within Neptune's primitive envelope of mass $\sim 1\ M_\oplus$ (Earth mass) no doubt played a major role in securing this event[9]. Triton's current orbital radius $\sim 14.2\ R_N$ (R_N = Neptune's equatorial radius) lies well inside the initial radius $\sim 25\ R_N$ expected for the proto–planetary envelope, judging from the radial extent of the other regular satellite systems.

Consider now in detail the processes which led to Triton's condensation within the protosolar cloud. Many of the basic physical and chemical features of the planetary system and regular satellite systems can be accounted for if there had existed a large, radial, turbulent kinetic stress $<\rho_t v_t^2>$ within each of the proto–solar/planetary clouds which formed these systems[3,5,7,8]. In the simplest representation, $<\rho_t v_t^2> = \beta\rho GM(r)/r$ where ρ is the local gas density, M(r) the total mass interior to radius r, G the gravitation constant, and $\beta = 0.107$ is the turbulence parameter[10,11]. The total radial stress at any point in the cloud is then

$$p_{tot} = p_{gas} + <\rho_t v_t^2>,$$

where $p_{gas} = \rho\mathcal{R}T/\mu$ is the usual gas pressure, T the temperature, μ the molecular weight, and $\mathcal{R}$ is the gas constant. Typically, $<\rho_t v_t^2> \sim 30\ p_{gas}$ near the outskirts of the cloud, meaning that the convective motions are strongly supersonic there. The inclusion of turbulent stress has two very important consequences. First, on the physical side, it causes a rotating and gravitationally contracting cloud to rid its excess spin angular momentum by shedding a discrete family of orbiting gas rings. The orbital radii R_n (n = 1,2,3,...) of these gas rings, of nearly equal mass m, are related to the mass M_{cl} and moment–of–inertia coefficient f (~ 0.01) of the parent cloud by the equations

$$R_n/R_{n+1} = [1 + m/M_{cl}f]^2 . \tag{1}$$

If the contraction takes place homologously, meaning that both m/M_{cl} and f are constant, then the radii R_n form a geometric sequence, similar to that of the observed planet/satellite orbital radii.

Second, because the gas pressure in the outer layers of the turbulent cloud ($\beta = 0.107$) is very much less than that in conventional non–turbulent models, carbon chemistry is shifted into a region where the formation of CO_2 and solid carbon C(s) becomes possible. At low temperatures, the carbon activity a_C is controlled by the reaction $CH_4 \rightleftharpoons 2H_2 + C(s)$. We have

$$a_C = [p_{CH_4}/p_{H_2}^2]K_1(T) , \tag{2}$$

where the p_i's denote partial pressures and $K_1(T)$ is the equilibrium constant[12]. For a fixed ratio of CH_4 to H_2, a_C varies as $1/p_{H_2}$. In a gas of solar composition[13], graphite can form ($a_C \geq 1$) only if $T \lesssim 473$ K and $p_{H_2} \lesssim 4 \times 10^{-8}$ bar. At 470 K, a_C for the conventional solar adiabat[12] is 5×10^{-4}, since $p_{H_2} \sim 2 \times 10^{-4}$ bar is so large. That is, graphite formation is impossible here.

Within a turbulent cloud of solar composition whose equatorial radius matches that of Neptune's orbit, a_C (470 K) = 0.82, when $p_{H_2} = 7.0 \times 10^{-8}$ bar. Graphite formation is thus almost possible. For such a cloud, however, having heavy element abundance $Z = Z_\odot$, the total mass of rock and ice condensate within the gas rings shed at the orbits of J, S, U, and N are 9.5, 7.1, 5.2, and 3.8 $M_\oplus$, respectively. If the condensate in each ring were to aggregate into a single planetary core, the masses of the cores would fall short of the values measured by Pioneer 11 (ref. 14), or deduced from planetary interior models[15], by factors of 2.1, 2.6, 2.5, and 4.2, respectively. The same problem occurs in the Galilean system of satellites, where eqn. (1) yields a mass for Io of 3.4×10^{25} g. This falls short of the observed mass[16] by a factor of 2.6. To remedy this deficiency, which is probably due to the simplified treatment of supersonic turbulent stress, it was decided to increase Z by a factor of 2.5. Under these circumstances $a_C > 1$ for all cloud equatorial radii $R_e \gtrsim 3{,}300\ R_\odot$, provided thermodynamic equilibrium is achieved.

Consider now the rate of production of CH_4, C(s) and CO_2 in a cloud which is initially composed of CO. The controlling reaction is $CO + 3H_2 \rightleftharpoons CH_4 + H_2O$. For simplicity, we assume a linear equation similar to the Temkin–Pyzhev rate equation for iron–catalysed NH_3 synthesis[17,18]:

$$dp_{CH_4}/dt = k_2\left[p_{CO} - p_{CH_4} p_{H_2O} / p_{H_2}^3 K_2(T)\right] .$$

Here k_2, K_2 are the rate and equilibrium constants. Collision theory[19] yields

$$k_2 = \frac{3\rho X_{Fe,f}}{\rho_{Fe} a_{Fe}} \left[\frac{\mathcal{R}T}{2\pi \mu_{CO}}\right]^{1/2} \left[1 + \frac{E_a}{\mathcal{R}T}\right] \exp\left[-\frac{E_a}{\mathcal{R}T}\right] , \qquad (3)$$

where $X_{Fe,f} = 0.487\ X_{Fe}$ is the mass fraction of free metallic iron (allowing for FeS formation), $\rho_{Fe} = 7.875$ g/cm^3, a_{Fe} is the iron grain radius, and $E_a = 21.3$ kcal/mole is the activation energy[20]. Although earlier calculations[21,22] assume that $a_{Fe} = 10^{-2}$ cm – a mean derived from studies of chondritic meteorites[23] – we feel that a much smaller value is likely to apply to the hot convective interior of the protosolar cloud. Unless $a_{Fe} \lesssim 10^{-5}$ cm, the rate of CH_4 production is negligible and, if $a_{Fe} \gtrsim 2 \times 10^{-6}$ cm, we cannot account for any free CH_4 ice on Pluto's surface[24] because H_2O enclathrates all the available CH_4. We therefore adopt $a_{Fe} = 10^{-6}$ cm.

Eqn. (3) can be integrated once the radial velocity $v_e = dR_e/dt$ and initial radius R_0 of the cloud are specified. Now for $R_e \leq R_* \simeq 426\ R_\odot$, the cloud's gravitational energy $\mathscr{E}_{grav} \simeq 3.3\ GM_{cl}^2/R_e$ exceeds the total energy $\mathscr{E}_{eqm}$ needed to establish a complete hydrostatic and thermodynamic equilibrium. Radial contraction is governed by the rate at which the excess energy $\Delta\mathscr{E} = \mathscr{E}_{grav} - \mathscr{E}_{eqm}$ can be radiated from the surface. Very roughly, $d(\Delta\mathscr{E})/dt \simeq -(GM_{cl}^2/R_e^2)v_e = \mathscr{L}$ where $\mathscr{L} = 2.82\pi\sigma_s R_e^2 T_{eff}^4$ is the luminosity[11], and $T_{eff} \simeq 361\ (R_*/R_e)^{0.9}$ K is the effective surface temperature. We obtain

$$v_e \simeq 0.0103\ [R_e/R_*]^{0.4}\ R_\odot/\text{yr}\ . \qquad (4)$$

We assume that eqn. (4) is also valid for $R_e \geq R_*$, noting that the formation of a small compact core at the centre can release sufficient energy to stabilize the rest of the cloud[3].

Fig. 1 shows the run of methane number fraction f_{CH_4} for a cloud whose initial radius is $R_0 = 7946\ R_\odot$. This radius was chosen so that the composition of the condensate in the gas ring shed at Neptune's orbit has a compressed density consistent with the observed mean density of the Pluto–Charon system (see below). Choosing $R_0 > 7946\ R_\odot$ yields a condensate which has too much CH_4 ice and too low a density. Now f_{CH_4} is taken to equal the maximum CH_4 fraction within the cloud of given size R_e. At the cloud surface, where T is least, the rate of production of CH_4 is negligible. In the deep interior, where the rate is large, the thermodynamically favoured state for C is CO. That is, there is a unique depth and temperature T_{max} where f_{CH_4} is a maximum. The values of T_{max} for cloud sizes R_e which match the orbits of J, S, U, and N are 458, 465, 470 and 484 K, respectively. We assume that convective mixing homogenizes the outer layers of the cloud, yielding a uniform composition having mean CH_4 fraction $\bar{f}_{CH_4} = f_{CH_4,max}$. Almost certainly, some CH_4 will be destroyed through downward mixing into regions where CO is dominant. That is, $\bar{f}_{CH_4}$ is probably less than $f_{CH_4,max}$. A more comprehensive study of the effect of mixing on the CH_4 level is outside the scope of this report.

The rate of production of solid carbon C(s) is assumed to be proportional to that of CH_4. This leads to $f_{C(s)} = f_{CH_4}[f_{C(s)}/f_{CH_4}]_{eqm}$, where $f_{C(s),eqm}$,$f_{CH_4,eqm}$ denote the corresponding equilibrium fractions of C(s) and CH_4 at temperature T_{max}. Lastly, the ratio f_{CO_2}/f_{CO} is assumed to equal its equilibrium ratio. This is valid owing to the fairly rapid rate of the gas phase reaction $CO + H_2O \rightleftharpoons CO_2 + H_2$ (ref. 25).

At the orbit of Neptune $f_{CH_4} = 0.153$, $f_{C(s)} = 0.111$ and $f_{CO_2} = 0.143$. These fractions enable us to calculate the abundances of anhydrous rock ($MgSiO_3$,Fe_3O_4,FeS,Al_2O_3,...), H_2O, etc., in the Neptunian gas ring, noting that O, which is normally tied up as H_2O in a CH_4–rich atmosphere, or between H_2O and CO in a CO–rich atmosphere[21,26], is now to be first apportioned to CO and CO_2. Assuming the Anders and Ebihara heavy element abundances[13], multiplied by the factor 2.5, the percentage masses of rock, H_2O, CH_4, CO_2 and C(s) are 1.321, 0.677, 0.201, 0.507 and 0.109%, respectively. All of these materials, except CH_4, fully condense from the gas phase, since the gas ring temperature $T_N = 27.4$ K is so low. Of the CH_4, 52.2% is encaged by H_2O ice, to form $CH_4 \bullet 5.75\ H_2O$, whilst only a modest 6.3% can condense out as solid CH_4 ice since the condensation temperature only just exceeds T_N (by 0.1 K!).

The mass fractions of the condensate at Neptune's orbit are thus: rock 0.4835, H_2O ice 0.2478, clathrated CH_4 0.0384, CH_4 ice 0.0046, CO_2 ice 0.1857 and graphite 0.0400. This is the predicted bulk composition of Pluto, Charon, and Triton, assuming that all 3 objects condensed from the Neptunian gas ring. No NH_3 ice is present since the rate of NH_3 synthesis in the protosolar cloud is negligible. That is, all nitrogen exists as N_2. Since no room remains for the incorporation of CO, N_2 and Ar in the H_2O ice, after the energetically favoured[27] enclathration of CH_4 has taken place, the satellites should contain very little trace of these species. That is, the atmosphere of Triton should consist mostly of CH_4.

Structural and evolutionary models may now be constructed to estimate the satellite mean densities $\bar{\rho}_{\mathrm{sat}}$. These calculations are described only briefly here. First, a set of cold chemically homogeneous models for Charon and Pluto were constructed having radii of 596 and 1142 km, equal to the observed values[28]. The assumed uniform temperature is $T_s = 45$ K (ref. 29). The values $\bar{\rho}_{\mathrm{Ch}} = 1.9984$, $\bar{\rho}_{\mathrm{Pl}} = 2.0744$ g/cm^3 so obtained have a mass–weighted average of 2.0649 g/cm^3, which coincides with the observed system mean $\bar{\rho}_{\mathrm{sys}} = 2.065 \pm 0.047$ g/cm^3. This justifies the choice $R_0 = 7946\ R_{\odot}$, mentioned earlier. Next, the cold satellite models were allowed to warm up under the influence of radiogenic heating and thermally evolved for a period of 4,600 Myr. This yielded a present–day temperature profile whose central temperature T_0, along with the central pressure P_0, is shown in Table 1. The corresponding values $\bar{\rho}_{\mathrm{sat}}$ are also shown. The densities are only slightly less than those of the cold, isothermal models. By choosing a slightly smaller initial cloud radius $R_0 \simeq 7890\ R_{\odot}$, one could achieve a slightly less icy, and hence denser, model. An estimate of the correct mean densities $\bar{\rho}_{\mathrm{corr}} = \bar{\rho}_{\mathrm{sat}} + 0.0066$ g/cm, whose system average coincides with the observed value, is shown in the last column. It should be mentioned that the model of Pluto reported here is cooler than that of McKinnon and Mueller[2]. This is partly due to a lower rock fraction (0.48 vs 0.73), which reduces chondritic heating, and partly because of a higher thermal conductivity, brought about mostly by the presence of graphite[30].

The final 3 rows of Table 1 list the computed properties of 3 different–sized models of Triton. The radii span the observed range $r_{\mathrm{Tr}} = 1{,}750 \pm 250$ km[31]. The surface temperature is 57 K (ref. 32). Triton is so large that, in the absence of internal convection, T_0 rises to 670 K after 2,800 Myr and equals 581 K at present age. That is, wide–spread melting of ice and internal differentiation of rock and ices would ensue, resulting in a substantial drop in mean density (from 2.2 to 1.8 g/cm^3). We suggest here that the presence of CO_2 ice prevents this outcome. CO_2 ice is a weakly bonded crystal whose isothermal compressibility[33] χ_{CO_2} at 150 K is some $2\frac{1}{2}$ times that of H_2O ice, for the pressures applicable to Triton's interior. The ratio χ_{CO_2}/χ_{H_2O} increases with T. We therefore suggest, following Lupo and Lewis' argument for weak CH_4 ice[34], that solid–state convection quickly wipes out any steep conductive temperature gradients inside Triton and, thereafter, controls the thermal evolution. To model this phenomenon we assume[35] that creep sets in as soon as T rises to 0.6 of the CO_2 melting temperature T_m (ref. 36).

On this basis, Triton has a central convective core covering ~ 65% of its mass. The temperature T_0, T_{core} at the centre and core edge are given in the Table, along with $\bar{\rho}_{sat}$ and the corrected value $\bar{\rho}_{corr}$. From these results we make the prediction that, if Voyager 2 finds Triton's true radius to be 1,750 + Δr km, the observed mean density $\bar{\rho}_{Tr}$ will satisfy the equation

$$\bar{\rho}_{Tr} = 2.20 + 3.00 \times 10^{-4}(\Delta r) + 2.0 \times 10^{-7}(\Delta r)^2 \pm 0.05 \text{ g/cm}^3.$$

The author thanks J.D. Anderson, J.R. Anderson, A.F. Moody and G.K. White for valuable discussions, and Telecom (Australia) for financial support.

Table 1 Structural properties of CO_2–rich model satellites

r_{sat} (km)	P_0 (kbar)	T_0 (K)	T_{core} (K)	m_{core}/m_{sat}	$\bar{\rho}_{sat}$ (g/cm^3)	$\bar{\rho}_{corr}$ (g/cm^3)
596	2.05	61	–	0.	1.993	1.999
1142	8.05	132	–	0.	2.068	2.074
1500	15.5	239	181	0.494	2.133	2.140
1750	23.0	271	180	0.649	2.196	2.203
2000	33.6	308	181	0.739	2.284	2.290

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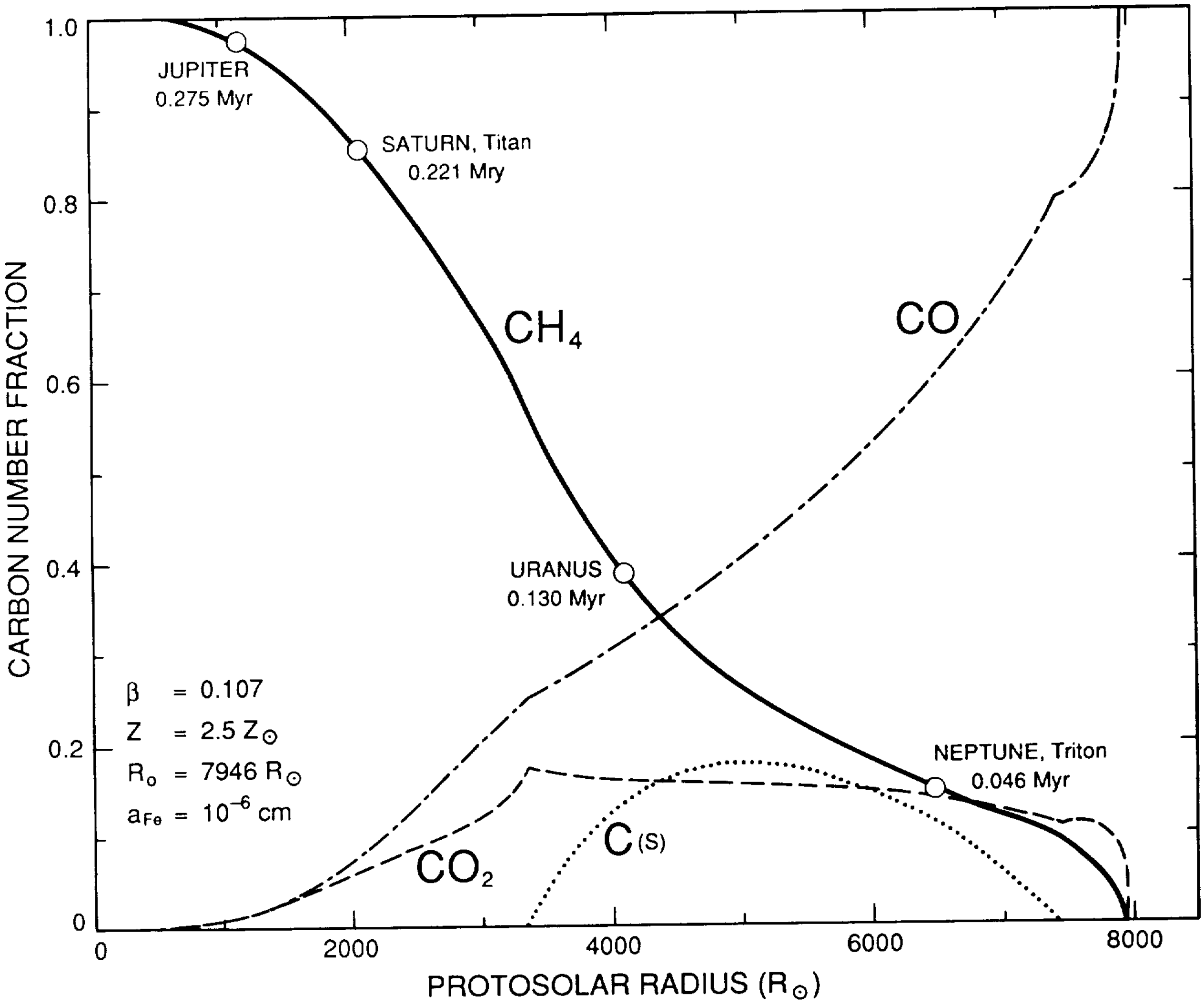

Figure 1. Relative number fractions f, in terms of total carbon, of CH_4, CO, CO_2 and C(s), in the outer layers of the turbulent protosolar cloud, plotted against cloud radius R_e, measured in units of $R_\odot$. C(s) means graphite. R_0 is the initial cloud radius, β the turbulence parameter[5,10], Z the total heavy element fraction, and a_{Fe} is the mean radius of the iron grains used in the calculation of the rate of catalytic production of CH_4 from the initial reservoir of CO.