**TITAN'S PHYSICAL AND CHEMICAL STRUCTURE: PREDICTIONS FOR A CAPTURE ORIGIN.**

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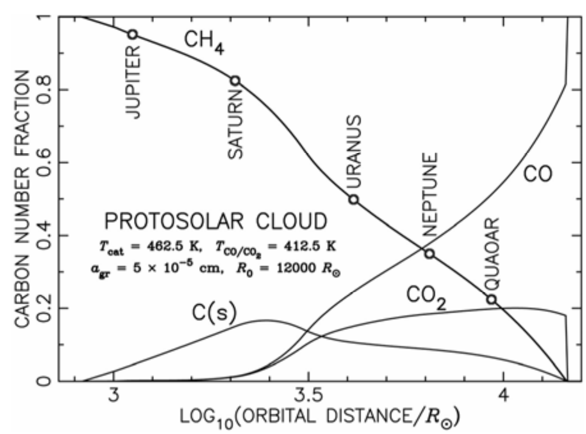
**Introduction:** The Cassini-Huygens mission has been sending back a steady stream of new data about Titan for over 2 years. Perhaps the most surprising discovery made by the Huygens probe was that the noble gases Ar, Kr, and Xe are almost totally absent from Titan's $N_2$-$CH_4$ atmosphere [1]. This means that the clathrate hydrates of Ar, etc were not part of Titan' s chemical inventory. The Cassini radar mapping and imaging science experiments found that the surface of Titan has very few impact craters. This means that the surface of Titan – once probably heavily cratered – has undergone profound change since the time it formed.

Here I report calculations for the bulk chemical composition and internal structure of Titan in readiness for measurements from the 4 scheduled gravity fly-pasts by Cassini to take place in 2006-2007. The calculations are based on the idea that Titan is a captured moon of Saturn [2,3]. That is, it is proposed that Titan initially condensed as a secondary planetary embryo within the gas ring that was shed by the protosolar cloud (hereafter PSC) at Saturn's orbit. Gas ring sheding is a central feature of the modern Laplacian theory of solar system origin [4,5]. It is the means by which the PSC (and also the proto-planetary envelopes of Jupiter, Saturn, Uranus and Neptune) disposed of excess spin angular momentum during gravitational contraction from beyond the orbit of Quaoar to present solar size.

**The Modern Laplacian Theory:** The mean orbital radii $R_n$ and masses $m_n$ ($n$ = 0,1,2,..) of the rings satisfy the equations $R_n/R_{n+1} = (1 + m_{n+1}/M_{n+1}f_{n+1})^2$. Here $M_n, f_n$ denote the residual mass and moment-of inertia factor of the cloud after shedding the $n^{\text{th}}$ ring. If the cloud contracts uniformly, so that $f_n$ and $m_n/M_n$ stay constant, then $R_n/R_{n+1}$ is also constant. We apply the above equations to the family of gas rings cast off by the proto-Saturnian cloud and choose $f_n$ = 0.01, $M_n \approx M_{\text{Sat}} = 5.685 \times 10^{29}$ g and $\langle R_n/R_{n+1}\rangle = 1.30$, which is the observed mean distance ratio from Mimas to Rhea. We obtain $m_n \approx 8.0 \times 10^{26}$ g. Next applying protosolar element abundances [6], the maximum mass of rock , $H_2O$ ice, $NH_3$ ice) that can condense in any gas ring is $m_{\text{cond}} \approx 0.0118 m_n = 9.4 \times 10^{24}$ g [7]. The mass $M_{\text{Ti}}$ of Titan exceeds $m_{\text{cond}}$ by a factor of ~14. We deduce that Titan cannot be a native moon of Saturn.

In order to predict the bulk chemical compostion of Titan, it is necessary to construct a model for the thermal evolution and structure of the PSC. A key feature of the model is the inclusion of a large turbulent stress arising from supersonic convective motions [7,8]. For a non-rotating cloud, this stress is given by $p_{\text{turb}} = \beta(r)\rho GM(r)/r$. Here $\rho = \rho(r)$ is the local gas density, $M(r)$ is the mass interior to radius $r$ and $\beta = \beta(r)$ is the turbulence parameter. The total pressure at each point is $p_{\text{tot}} = p_{\text{turb}} + p_{\text{gas}}$, where $p_{\text{gas}} = \rho \Re T/\mu$ is the usual gas pressure, $T$ is the temperature and $\mu$ is the mean molecular weight.

The PSC is assumed to acquire quasi-hydrostatic and thermodynamic equilibrium at equatorial radius $R_e = 12000 R_\odot$ and shed its first gas ring at the orbit of Quaoar ($9323 R_\odot$). Initially all carbon at the photosurface is present as CO. A steady conversion of CO to both $CH_4$ and graphite C(s) takes place through catalytic synthesis on the surfaces of small Fe-Ni grains deep within the atmosphere. Adopting a synthesis temperature $T_{\text{cat}}$ = 462.5 K and mean grain radius $a_{\text{gr}} = 5 \times 10^{-5}$ cm ensures that the condensate density at the orbit of Quaoar matches that of Phoebe (1.63 g/cm$^3$) and that all C(s) production ceases at orbital radius $\sim 830 R_\odot$. This is midway between the orbits of Jupiter and the main belt asteroids. It is assumed that rapid interconversion of CO to $CO_2$ takes place down to $T_{\text{cat}}$ – 50 K. The diagram below shows the computed distribution of carbon number fraction against present orbital distance.

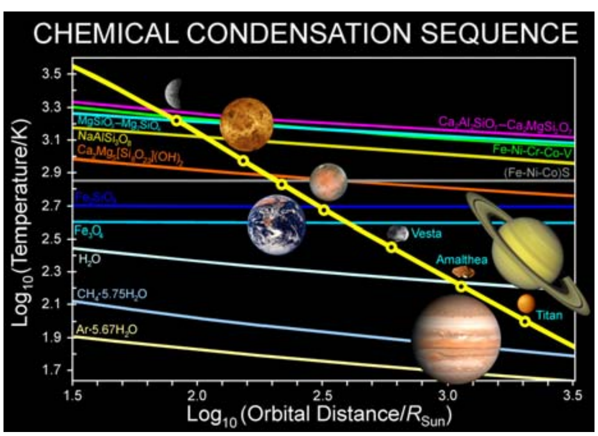



**The Gas Ring Condensation Model:** Because of the homologous contraction, the temperature $T_n$ and mean orbit pressure $p_n$ of each gas ring ($n$ = 0,1,2,..) vary with mean orbital distance $R_n$ according as $T_n \sim 1/R_n^{0.9}$ and $p_n \sim 1/R_n^{3.9}$. The constants of proportionality depend on the controlling parameters of the PSC.

These are chosen so that (i) the mean orbital spacings of the gas rings from Jupiter to Mercury matches the observed planetary spacings, and (ii) that the condensate bulk density $\rho_{\mathrm{cond}}$ at Mercury's orbit results in a planet of Mercury's physical size whose mean density equals the observed value, namely $5.43 \pm 0.01$ g/cm$^3$ [9]. In the diagram below, the heavy yellow locus shows a plot of the gas ring temperature versus orbital distance at the times of detachment of the rings. Also plotted are the condensation temperatures of the principal chemical species. These are computed for the pressure on the mean orbit of the local gas ring.

At Saturn's orbit, where Titan condensed, the gas ring temperature is $T_n = 94$ K and the mean orbit pressure is $4.9 \times 10^{-7}$ Bar. The condensate consists of rock (mass fraction 0.4925), water ice (0.4739) and graphite (0.0336). The rock is nearly anhydrous and consists mostly of $MgSiO_3$–$Mg_2SiO_4$ (mass fraction 0.4336), $SiO_2$ (0.0741), $Fe_3O_4$ (0.1768), FeS (0.1928), spinel (0.0320) and akermanite (0.0420). Its density at the present-day black body temperature at Saturn ($T_{\mathrm{Sat}}$ = 76 K) is 3.668 g/cm$^3$. The condensate mean density at is $\rho_{\mathrm{cond}}$ = 1.5226 g/cm$^3$. This is the predicted bulk chemical makeup of Titan.

**Titan's Capture from Solar Orbit:** It is proposed that Titan's capture was achieved by collision with 2 former Rhea-sized native moons of Saturn that once existed at orbital radius ~$17R_{\mathrm{Sat}}$ ($R_{\mathrm{Sat}}$ = 60268 km) and ~$24R_{\mathrm{Sat}}$. [7]. Much of the material of those lost moons is now buried in Titan's upper icy mantle. Hyperion is a surviving remnant. The lost moons consist of rock (mass fraction 0.33), $H_2O$ ice (0.37), $NH_3$ ice (0.24) and clathrated $CH_4$ ice (0.06). It is these buried ices which are the source of Titan's present atmosphere. The estimated total mass of $NH_3$ is $0.008M_{\mathrm{Ti}}$. The rock associated with the lost moons is predicted to be the source of anomalies in Titan's gravity field [3,10].




**Titan Structural Models:** A suite of thermally evolved structural models of Titan has been constructed for the predicted compositional mix, ignoring the new material acquired during capture. The mean radius and density of Titan are taken to be $R_{\mathrm{Ti}}$ = 2575 km and $\rho_{\mathrm{Ti}}$ =1.881 g/cm$^3$. A chemically uniform model has mean density $\langle\rho\rangle$ = 2.098 g/cm$^3$ and axial moment of inertia factor $C/MR^2$ = 0.384. This model is clearly too dense. A 2-zone model possessing a rock-graphite core of mean temperature 600 K has $\langle\rho\rangle$ = 1.939 g/cm$^3$ and $C/MR^2$ = 0.316. If the $H_2O$ ice mass is enhanced by a factor $E_{\mathrm{H2O}}$ = 1.137, we obtain $\langle\rho\rangle$ = 1.881 g/cm$^3$ and $C/MR^2$ = 0.317. Lastly, a 3-zone differentiated model was constructed by allowing the FeS-Ni-NiS component of the rock (mass fraction 0.2128) to form a solid core. Again choosing $E_{\mathrm{H2O}}$ = 1.207, so that $\langle\rho\rangle = \rho_{\mathrm{Ti}}$, we obtain $C/MR^2$ = 0.311.

**Influence of a predicted mass anomaly:** It is predicted that Cassini may discover anomalies in the gravity field of Titan due to the material acquired during capture [3,10]. Titan will reorient itself so that any mass excess is located in the equator and on the line joining the centres of Titan and Saturn [11]. Let $m_{\mathrm{anom}}$ denote the mass excess and $\delta = m_{\mathrm{anom}}/M_{\mathrm{Ti}}$. For Titan, the gravitational coefficients $J_2$ and $C_{22}$ are related to the undisturbed coefficients $J_{2,0}$ and $C_{22,0}$ by the equations $J_2 = J_{2,0} + \frac{1}{2}\delta$, $C_{22} = C_{22,0} + \frac{1}{4}\delta$. Hydrostatic equilibrium yields $C_{22,0} = 0.3\,J_{2,0}$ [12]. The table below gives predicted values of $C_{22}$ and $J_2$ for a range of $\delta$ values, derived for $C/MR^2$ of the 2-zone Titan model.

| $C/MR^2$ | $10^5 C_{22,0}$ | $10^5\delta$ | $10^5 C_{22}$ | $J_2/C_{22}$ |
|---|---|---|---|---|
| 0.317 | 0.831 | 0 | 0.831 | 3.33 |
| 0.317 | 0.831 | 1 | 1.08 | 3.02 |
| 0.317 | 0.831 | 2 | 1.33 | 2.83 |

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