



## ABLATION AND CHEMISTRY OF METEORIC MATERIALS IN THE ATMOSPHERE OF TITAN

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### ABSTRACT

We compute the input of meteoric materials expected on Titan, and integrate this dust model with an ablation model and a comprehensive chemical model, investigating the effects on the atmosphere and surface. We find that a water deposition of ~10-100 times the expected interplanetary dust flux /7/, or a recent large impact, is required to produce the observed CO<sub>2</sub> abundance /2/. Ionisation due to meteoric activity is not likely to be higher than that due to other sources.

### INTRODUCTION

Previous workers /1,2,3/ have considered the effects of meteoric materials in Titan's atmosphere on ion density and oxygen chemistry. Typically, the meteoric input has been assumed to be similar to that of the Earth, with a passing mention of Saturn's rings. We take a more rigorous approach to generating the meteoric input, and investigate its implications for oxygen chemistry, surface composition, ionisation and stratospheric condensates.

### DUST MODEL

In order to calculate the interplanetary dust flux into Titan's atmosphere two parameters were needed: the spatial number density of particles at 10 AU and their speed distribution. The number density at 10 AU was generated from an expression for the dust flux at 1 AU /4/, and the Pioneer 11 observation that the spatial density remained constant from 1 AU to 18 AU /5/. In order to assess the speed of the meteoroid population the Erickson meteor speed distribution /6/ was scaled from 1 AU to 10 AU. The gravitational enhancement by Saturn, and then by Titan, was applied along with compensation for the motion of Titan around Saturn. The flux onto Titan was binned into 72 angular bins and twenty speed and size bins. This allowed the flux to be evaluated at different points on Titan, taking account of motional effects. The model shows that the leading face flux is enhanced by a factor of ~20 from that on the trailing face. The globally-averaged mass flux onto Titan is  $9.93 \times 10^4 \text{ kgm}^{-2}\text{s}^{-1}$ , and the total accretion rate is 5700 tonnes /year /7/, compared to 40,000 tonnes/year ( $\sim 2.5 \times 10^{15} \text{ kgm}^{-2}\text{s}^{-1}$ ) for Earth /8/.

Work is continuing on estimation the contribution of Saturnocentric particles. Contrary to previous suggestions /2,3/ we assert that ring particles make no contribution, since there are no mechanisms adequate to increase their orbital energy, and (D.Hamilton, personal communication) the inner satellites shield Titan from the rings. Ejecta from impacts of interplanetary material on the outer satellites Hyperion, Iapetus, and Phoebe may add to the mass influx rate at a similar level to the interplanetary flux.

### ABLATION MODEL

Explicit numerical integration of the equation of motion using a 7th order Gear Method (favoured in previous work /9/) is used to calculate the flight paths of particles entering the atmosphere. The thermal histories of particles during aerobraking are calculated using a standard energy balance equation for an isothermal particle /eg 10/, namely

thermal energy = energy input by drag + solar insolation - radiated energy - ablation

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and is expressed:

$$\frac{4}{3}\pi r^3 \rho_m c \frac{dT_m}{dt} = \frac{\Lambda}{2} \pi r^2 \rho_a v^3 + \pi r^2 S(1-A) - 4\pi r^2 \epsilon_{\text{rad}} \sigma T_m^4 + L \frac{dm}{dt}$$

where:  $r$ ,  $\rho_m$ ,  $c$ ,  $T_m$ ,  $A$ ,  $\epsilon_{\text{rad}}$ ,  $L$ ,  $m$  are respectively the meteoroid's radius, density, specific heat capacity, temperature, albedo, emissivity, latent heat of vaporization and mass;  $\rho_a$  is the atmospheric density,  $v$  is the particle velocity relative to the atmosphere,  $S$  is the solar constant and  $\sigma$  is the Stephan-Boltzmann constant.  $\Lambda$  is a measure of the efficiency of energy transfer and has been calculated using the method of Hood and Horanyi /11/ for the hyperthermal regime.

The ablation profiles for each particle are computed by relating the mass loss rate to the vapour pressure of the particle's material at temperature  $T_m$ . These profiles are summed over mass, velocity and trajectory distributions to produce the deposition profiles for the leading and trailing faces of Titan.

Figure 1 shows the calculated profiles for 100% water-ice particles. The fine structure in the profiles results from coarseness in the trajectory and velocity binning: the important features are that the peak ablation (and hence water deposition) occurs at an altitude of  $\sim 700$  km, over an altitude range of a few scale heights, and that an order of magnitude more water is deposited on the leading face than on the trailing face. Fluxes on polar regions (where  $\text{CO}_2$  abundance is lower than near the equator) are only slightly higher than the trailing-edge flux.

Figure 2 shows the temperature profiles for silicate grains of 3 sizes on the leading face of Titan: the particles are heated to a high temperature, then the mass loss by ablation holds the temperature constant. Similar effects occur for ice meteoroids, but at a lower temperature.

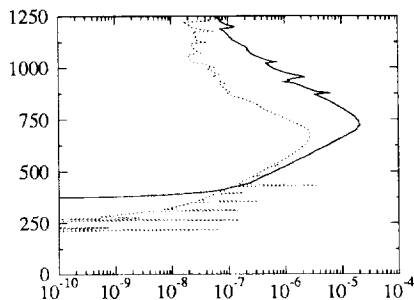


Fig.1. Leading and trailing face deposition profiles for interplanetary meteoroids of 100% water ice. Ordinate is altitude in km, abscissa is deposition in  $\text{kgm}^{-2}\text{s}^{-1}$  per 6km altitude bin. Solid line is for the leading face, dotted for the trailing face.

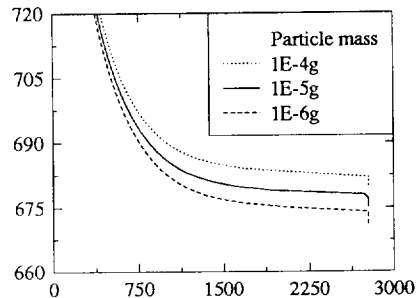


Fig.2. Temperature profiles for 100% silicate interplanetary meteoroids. Ordinate is altitude in km, abscissa temperature in K.

### CHEMICAL MODEL

The vertical distribution of 43 compounds in Titan's atmosphere has been calculated using a 1-D numerical model /12/ covering the altitude range 40-1432 km. The model features a comprehensive treatment of photochemical, eddy diffusion and condensation processes.

The low temperatures in Titan's atmosphere lead to a strong condensation sink for most compounds. While the hydrocarbon and nitrogen compounds' mixing ratios observed by Voyager 2 can be explained by the  $\text{CH}_4$  and  $\text{N}_2$  chemistry prevailing in this atmosphere, the  $\text{CO}_2$  would be removed by condensation in under  $5 \times 10^4$  years /2/ unless it could be replenished.

$\text{CO}_2$  can be formed by the reaction  $\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}$ . Production of OH by a cycle involving  $\text{CO}_2$  dissociation, forming  $\text{O}(^1\text{D})$ , which in turn reacts with methane to generate OH, is largely inhibited by hydrocarbon shielding of UV light. Thus, to explain the observed  $\text{CO}_2$  stratospheric mixing ratio /14/ of  $1.3 \times 10^{-9}$ , it is necessary to invoke an external source rich in oxygen bearing material /2,13/, typically meteoric water vapour which is photolysed into OH in the mesosphere and thermosphere.

Without an oxygen input, the chemical model suggests a  $\text{CO}_2$  abundance of  $1 \times 10^{-12}$ , namely the saturation limit at the tropopause. If we deposit  $\text{H}_2\text{O}$  vapour in the atmosphere assuming the model leading-face interplanetary flux ( $2.23 \times 10^{-15} \text{ kgm}^{-2}\text{s}^{-1}$ ) only, we find (Fig.3.) that the  $\text{CO}_2$  abundance is still too small.

If we enhance the H<sub>2</sub>O mass flux by a factor of 200, the required CO<sub>2</sub> abundance is met, but the water vapour concentration in the atmosphere would be higher than its non-detection would suggest, and the CO abundance begins to push against the observational limits /15/ (Fig. 4.,5.). However, since outer solar system material is likely to contain ices other than water ice, we also investigated a comet-like composition of 90% H<sub>2</sub>O, 7% CO, and 3% CO<sub>2</sub>: the input of only ~20 times the leading face flux interplanetary mass flux of this material agrees well with the observed abundances of all three compounds. We note that the oxygen chemistry produces other compounds (HCO, H<sub>2</sub>CO, CH<sub>2</sub>CO) at rates of  $1 \times 10^5$  to  $1 \times 10^7$  cm<sup>-2</sup>s<sup>-1</sup>, about ~100 times higher than suggested earlier /13/: if abundances are similarly higher, these compounds may be detectable by current groundbased techniques.

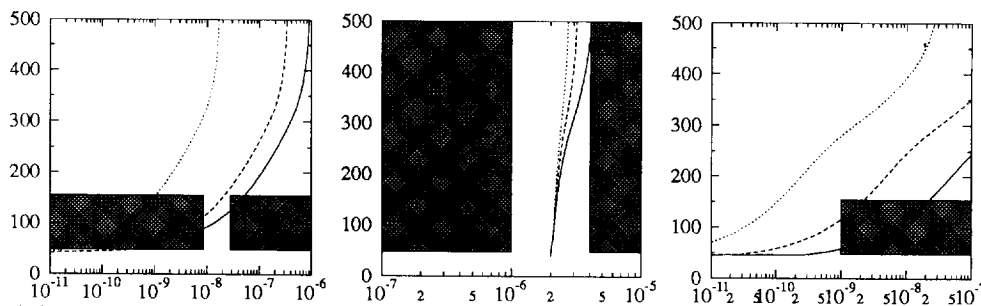


Fig 3,4,5. Mixing ratio (abscissa) profiles versus altitude (ordinate) for CO<sub>2</sub>, CO and H<sub>2</sub>O respectively, as predicted by the model for interplanetary-only leading-face flux H<sub>2</sub>O (dotted), 200 x H<sub>2</sub>O flux (solid), and 20 x Halley composition (dashed). Shaded regions denote mixing ratios not permitted by observations, although note that the H<sub>2</sub>O limit is uncertain.

The models with CO<sub>2</sub> mixing ratio in the observed range suggest the CO<sub>2</sub> condensation flux to the surface should be  $2\sim 5 \times 10^6$  cm<sup>-2</sup>s<sup>-1</sup>. This CO<sub>2</sub> flux is about an order of magnitude higher than that found earlier /2,13/, presumably due to the different treatment of condensation and eddy diffusion processes in the models, and the lower CO mixing ratio /15/ used in our model /12/. Our required meteoric water supply is correspondingly higher, although since back reactions of H<sub>2</sub>CO, CH<sub>2</sub>CO etc. into CO<sub>2</sub> are not modelled in the current model, the actual required water fluxes are probably lower than those stated above by a factor 2~5.

The above considerations assume a steady state. We note, however, that a large, recent impact could project large amounts of crustal (presumably water-bearing) material high into Titan's atmosphere, leading to a temporarily high CO<sub>2</sub> abundance. An enhanced water flux into the atmosphere (or the residue from a recent impact plume) perhaps make the recent identification /17/ of water ice in the stratosphere easier to understand.

## SILICATES AND IONS

One (controversial) interpretation of near-IR spectra of Titan, which appear to sense the surface, is that the dominant surface materials are anhydrous silicates /18/. As cryovolcanic eruption of anhydrous materials seems unlikely, we suggest meteoric deposition is the most plausible source. As seen in Fig 2., meteoric particles attain high enough temperatures to be dehydrated during entry, although we note that the meteoric flux required to exceed the deposition of photochemical organics ( $\sim 2 \times 10^9$  cm<sup>-2</sup>s<sup>-1</sup> flux of liquid ethane, and  $\sim 7 \times 10^8$  cm<sup>-2</sup>s<sup>-1</sup> for solid acetylene /16/) seems improbably high.

Following work by Ip /1/, Grard /3/ has suggested that meteors could cause an ionised layer on Titan at ~500km, with an electron density of  $\sim 1 \times 10^5$  cm<sup>-3</sup>. This could have prevented detection of lightning spherics by Voyager 1, although Voyager placed upper limits on electron densities at two points at  $3\sim 5 \times 10^3$  cm<sup>-3</sup>. Grard's estimate was based on an electron production of 0.1 cm<sup>-3</sup>, an *upper limit* for Earth. Although the oxygen chemistry considerations suggest that the mass flux on Titan may be 4~100x that of Earth, we find Grard's (entirely hypothetical) layer unlikely - the larger scale height on Titan (50km vs. 6km on Earth) means meteoric ions are distributed over a larger volume (by a factor of ~10). Also, our velocity distribution suggests a mean speed of  $\sim 9.5$  kms<sup>-1</sup> for interplanetary meteors on Titan (only  $\sim 3$  kms<sup>-1</sup> for Saturnocentric material), whereas terrestrial meteors have a mean speed of  $\sim 16$  kms<sup>-1</sup>. Ionisation efficiency (the number of free electrons yielded by each ablated meteor atom) scales /19/ as  $v^{3.5}$ , or 10~1000 times less efficient on Titan. Thus we find no reason to suspect an electron density as high as that suggested by Grard /3/, nor, by implication 'hidden' lightning.

## CONCLUSIONS

We find that a model of interplanetary dust is insufficient to supply the observed CO<sub>2</sub> abundance in Titan's atmosphere. A composition-dependant enhancement of 4~100, perhaps from Saturn's outer satellites, is required. We suggest that a search for additional oxygen compounds in Titan's atmosphere may be fruitful, especially on the leading face. Solid surface material on Titan should contain a small fraction of meteoric dust (silicates) and condensed oxygen species (mostly CO<sub>2</sub>) of meteoric origin. Silicate meteoric material is probably dehydrated, and meteoric ionisation is not as high as previously suggested.

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