ON THE EXCESS THERMAL FLUXES OF TITAN AND SATURN

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Abstract. The assumption of a recent (3.5–10 thousand years ago) explosion of the electrolysis products of Titan's ices suggests a common explanation for many peculiar features of Saturn's system.

In particular, the high excess luminosity of Saturn is due, possibly, to its having accreted a part of the material lost by Titan. The accretion of this material from Saturn's rings is continuing at present.

The crucial experiment to support the possibility of a recent Titan's ices explosion would be detection of excess heat flux. At the present time it could constitute 1.5–15% of the solar radiation flux absorbed by this satellite.

1. Introduction

Due to its internal heat sources (radioactivity, gravitational separation of matter etc.), Earth radiates into space $\sim 0.05\,\mathrm{W\,m^{-2}}$ (Monin, 1979), and the Moon, ~ 0.014–$0.018\,\mathrm{W\,m^{-2}}$ (Keihm and Langseth, 1977) which is negligible compared to the solar flux of $1360\,\mathrm{W\,m^{-2}}$ at 1 AU and could not be detected by present day instrumentation from space.

In contrast to the Earth and Moon, the radiation given off by the giant planets is at least comparable to the energy received by them from the Sun. Jupiter emits twice, and Saturn and Neptune almost twice more energy than that absorbed by them from the Sun (Gautier and Courtin, 1979). The power of the internal source of Uranus, if it exists at all, should not be larger than 1/3 of the incident solar radiation flux.

The nature of the internal heat sources in the giant planets is at present not known. A number of possibilities have beena analyzed for Jupiter and Saturn (Hubbard and Smoluchowski, 1973) including meteoritic bombardment, internal heat accumulated during the rapid initial collapse of the planet, and the potential energy released in the course of subsequent slow contraction. It appears that the latter could well be at present the major energy source: indeed, to provide the observed luminosity, it would be sufficient for Jupiter's radius to decrease by $\sim 1\,\mathrm{mm\,yr^{-1}}$.

For Saturn with its lower mass such a simple explanation is apparently invalid (Pollack, 1978). Here, however, the internal temperature is lower than that in Jupiter, and energy can be released in the gravitational separation of the metallic phases of hydrogen and helium. Therefore, Voyager 1 was expected to detect a deficiency of helium in Saturn's atmosphere compared to Jupiter. These expectations were not confirmed. The He/H_2 ratio turned out at first to be the same (Beatty, 1981) leaving us without explanation the enhanced luminosity of Saturn; (but after completion of this paper, a nearly two-fold deficiency of He in Saturn, detected by Voyager 1, was announced by Hanel *et al.*, 1981). The Saturn system, as pointed out previously (Drobyshevski, 1980b,

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1981; hereafter referred to as Paper 1), possesses also a number of other peculiarities which distinguish it among other systems (for details see below).

It is possible to explain these features within a common viewpoint if one assumes the possibility of a recent explosion of Titan's ice envelope saturated with the products of volumetric electrolysis of ice. This hypothesis implies in particular, that Titan itself, in contrast to other Moonlike bodies, should radiate at present more energy than it is receiving from the Sun. It is natural to assume that Saturn's excess luminosity, just as some other features of the system, could also be due in a more or less extent to the recent explosion of Titan's ices.

We intend to show here that ejection of material from Titan with a subsequent accretion of a fraction of it by Saturn could account for the observed excess radiation of the planet. In addition, the expected excess heat flux from Titan will be evaluated. It was found that it may make up 1.5–15% of the absorbed solar energy flux which is substantially larger than the Moon's excess flux.

2. Explosion of Titan's Ices: Energetics and Implications. Voyager 1 Data

The presence of a sharp peak at $\Delta_{\min} \lesssim 0.5$ AU in the distribution of comets in the minimal interorbital separation $\Delta_{\min}$ of Saturn's family discovered by Konopleva (1980) among the long-period comets ($P \geqslant 200$ yr) implies that the comets responsible for this peak are very young. The semimajor axis of Saturn's eccentric orbit completes one turn every 47 000 yr so that the age of the peak cannot exceed $\sim 12\,000$ yr (Paper 1).

An analysis of the longitudinal distributions of $\Delta_{\min}$ for the same comets but for different intervals of $\Delta_{\min}$ supports unambiguously the hypothesis of the peak's comets having been ejected from Saturn's sphere of action.

The simplest explanation for such an event which comes immediately to mind is a recent explosion of Titan's ice envelope saturated with the products of volumetric electrolysis of the ice. Within this framework one can understand the reasons for the existence of a reservoir of cometary nuclei beyond Jupiter's orbit, find an explanation for the 20–50 times increase of the micrometeoritic flux in the recent $\sim 10^4$ yr, eliminate the difficulties associated with the assumption of a cosmogonic age of Saturn's rings and of Titan's atmosphere, develop a new approach to solving the problem of the origin of the broad Cassini gap, of the photometric asymmetry of Saturn's satellites, of Saturn's magnetic field proper, etc. (Paper 1).

The idea of a recent explosion of Titan's ices has allowed a number of observationally verifiable predictions to be made.

Some of these predictions have been confirmed during the Voyager 1 fly-by through Saturn's system in November 1980, although the scientific program of the spaceprobe was not suited for their testing.

Indeed, it turned out in complete agreement with the idea of a recent explosion that Titan's atmosphere is very thick and opaque, that apart from nitrogen and a small ($\sim 1\%$) amount of hydrocarbons it contains HCN which may be a product of frozen high temperature equilibrium, that the radius of Titan's surface ($R_s \approx 2570$ km) is markedly smaller than the value accepted until then ($R_s = 2700$ km) and even smaller than that of Ganymede, as it should be bearing in mind their similar eruptive history (see also Drobyshevski, 1980c; Paper 2) and the small difference in their masses. Voyager's data do not permit one to exclude a possibility that the Titan's atmosphere contains also CO – the product of the ices explosion – as not a minor constituent.

The fine structure of the rings which have been discovered to be made up of hundreds of thin, sometimes elliptical and even intertwining ringlets (Kerr, 1980) evidences a lack of equilibrium and a continuing relaxation of the system – i.e., its young age.

Voyager 1 discovered near ring F consisting, as it turned out, of three narrow (~ 20 km wide) intertwined ringlets large rocks a few tens of km in size. These rocks play an essential role in the dynamics and stability of the rings. The smallest known satellite orbits just outside A ring and is of a few tens km in size.

The spatial resolution in the rings images obtained by Voyager 1 did not exceed ~ 10 km per pair of lines, thus making it impossible to insist on the existence of, say, kilometer-size rocks as well. However the discovery of larger rocks governing the stability of the F rings, as well as the fact itself of the rings being made up of a multitude of small and, hence, relatively stable ringlets which, just as in the case of ring F, requires the action of an additional stabilizing factor makes the existence of such bodies highly probable (Smith *et al.*, 1981).

All this supports our hypothesis of the existence of a second, km-size, population of Saturn's rings which represents fragments of nonexploded surface layers of Titan's ice envelope and should govern the dynamics and energetics of the rings (Paper 1).

A recent explosion of the electrolysis products in Titan's ice envelope in which $\sim 2 \times 10^{29}$ J was released should have resulted in an evaporation of the ices and their partial loss (as follows from a comparison with Ganymede which is close in mass and also suffered an explosion in the past, about 13% of the initial mass of Titan, $M_{0\text{Tit}} = 1.56 \times 10^{26}$ g, was lost). A consideration of the probable energy balance taking into account the energy needed to heat the ices, their evaporation and the loss of material into space (see Table I) leaves for the energy of the remaining heated liquid water $\lesssim 0.15 \times 10^{29}$ J, an amount which should be compared with the energy contained in the same mass of liquid water heated, say, to 373 K ($\sim 0.24 \times 10^{29}$ J). From this it follows that part of the energy stored in the heated liquid water had apparently been expended already during the final stage of escape of Titan's mass into space via evaporation of the atmosphere.

A purely radiative cooling of the water remaining on Titan (~ 42% by mass) from the boiling (~ 373 K) down to freezing temperature (273 K) should have been continuing ~ 18 000 yr. Comparing this time with the maximum age of Saturn's long-period comet family ($\lesssim$ 12 000 yr, see above) one feels justified in assuming that Titan's surface is still covered by liquid water ($T \gtrsim 273$ K) (Drobyshevski, 1980a).

TABLE I

A crude estimate of Titan's energy balance after ice envelope explosion (present day Titan mass, $M_{\text{Tit}} = 1.36 \times 10^{26}$ g (Smith, 1980), initial mass $M_{0\text{Tit}} = 1.56 \times 10^{26}$ g (from comparison with Ganymede, Papers 1 and 2), half of $M_{0\text{Tit}}$ having been ices).

Released in the explosion of electrolysis products of 1/5 of all ice	2×10^{29} J
Expended in heating the initial ice envelope from $T_m \approx 170$ K to melting point $T \approx 273$ K	0.14×10^{29} J
Expended in melting 80% of initial ice envelope	0.21×10^{29} J
Left for the heating of water, its evaporation and heating of the vapor	1.65×10^{29} J
Expended in removing from Titan $M_{\text{env}} \approx 0.13 M_{0\text{Tit}} = 0.20 \times 10^{26}$ g (from comparison with Ganymede, see Papers 1 and 2) at the expense of the energy stored in the hot vapor envelope and released in its condensation	1.5×10^{29} J
Remained as the energy of heated water (up to $T \approx 330$ K)	0.15×10^{29} J
Which should be compared at least with the energy released by the remaining water (0.58×10^{26} g) in cooling from $T = 373$ K down to $T = 273$ K	0.24×10^{29} J

Whence it follows that not only the energy stored in the water vapor but also a considerable part of that contained in the heated condensed water was expended in the evaporation of the atmosphere.

3. Microwave Observations of Titan: Some Conclusions

The problem of the existence of a liquid water surface could in principle be solved by microwave measurement of the brightness temperature T_B. As is well known, such measurement allowed to establish that the surface of Venus blanketed by an opaque atmosphere is heated to ~ 750 K.

As of the beginning of 1980, only three microwave measurements of the brightness temperature were available: $T_B = 87 \pm 13$ K at $\lambda = 6$ cm (Jaffe *et al.*, 1979); $T_B = 99 \pm 35$ K at $\lambda = 3.8$ cm (Briggs, 1974); $T_B = 220 \pm 40$ K at $\lambda = 3.3$ mm (Conklin *et al.*, 1977; all these measurements are reduced to a radius of 2700 km). It being unclear how to reconcile these results, doubt can be cast on their correctness. The assumption of a liquid water surface with an emissivity low in the cm range while increasing for the mm waves allowed to eliminate the controversy, the surface temperature T_s turning out to be close to 273 K. Such a high temperature at the base of the atmosphere assumed the latter to be very thick and massive (Paper 1, Drobyshevski, 1980a).

In June 1980, however, Roelling and Houck (1980) reported $T_B = 86 \pm 12$ K for $\lambda = 1$ mm which agreed with the previous cm range measurements and cast doubt on the $\lambda = 3.3$ mm observations.

Finally, in December 1980 Jaffe *et al.* (1980) published the results of T_B measurements with the Very Large Array consisting of up to 14 radiotelescope dishes with a base of 25 m to 20 km. The experiment was performed at $\lambda = 6$ cm, 2 and 1.3 cm. Independent measurements carried out at $\lambda = 2$ and 1.3 cm yielded for the brightness temperature the values $T_B = 89 \pm 10$ K and $T_B = 52 \pm 35$ K, respectively, while from the total flux at $\lambda = 2$ cm one could derive $R_s = 2440 \pm 500$ km. These results (Jaffe *et al.*, 1980) can be best reconciled by assuming that $R_s = 2400 \pm 250$ km and $T_B = 87 \pm 9$ K for all three wavelengths (reducing to $R_s = 2700$ km we obtain $T_B = 69 \pm 7$ K).

Thus all the five available measurements at $\lambda = 1$ mm, 1.3, 2, 3.8, and 6 cm, except the $\lambda = 3.3$ mm observation, appeared to be mutually compatible and yielding the same temperature close to 85 K which would set in under conditions of equilibrium with solar radiation. One could then conclude that this value is the temperature of the surface with no liquid water coverage.

The sounding of the atmosphere effected during Voyager 1 occultation by Titan at $\lambda = 3.6$ cm and 13 cm in November 1980 yielded, however, a somewhat different result. This experiment provided finally unambiguous information on the atmosphere structure. Just as predicted basing on Titan's ice explosion assumption, the atmosphere turned out to be so dense that the radiowaves which penetrated it down to $R \approx 2570$ km gave $p \approx$ 1.6 atm and $T \approx 93$ K (Beatty, 1981; Tyler *et al.*, 1981). The Voyager 1 team believes this level to be the real condensed surface of Titan. Nevertheless, some doubt remains on where actually is the surface and what are the conditions on it. It is clear also that previous Earth-based microwave measurements likewise cannot yield a reliable information on the surface properties. It follows only from these observations, in particular, from a comparison of the small value of the radius, $R = 2400 \pm 250$ km obtained by Jaffe *et al.* (1980) by fitting T_B to the total energy flux with the radius derived from the Voyager 1 data ($R \approx 2570$ km) that the atmosphere is apparently so dense as to produce a limb darkening effect in the microwave range (such an effect is observed for Venus). Earth-based microwave methods appear thus to be incapable of providing unambiguous information on the surface properties in the foreseeable future. First, the radiation intensity decreases drastically as one goes to long wavelengths ($\sim \lambda^{-4}$) which would be needed to penetrate deeper into the atmosphere; second, the emissivity of the surface if it is covered by liquid water would be so low that T_B could remain at the ~ 100 K level (although a maximum in the $T_B(\lambda)$ relationship could appear as a result of the atmosphere temperature increasing as one approaches the surface).

The most complete information on Titan's structure could be collected by a probe, particularly if it would be capable of floating in a dense atmosphere at different levels (see, e.g., Blamont, 1978). This possibility may become realized, however, only in the late 80's (Colin, 1978).

As for the nearest future, detection of an excess radiation in Titan's energy balance would be of crucial importance for the hypothesis of a recent explosion of Titan's ices and, thus, for the fundamental problem of the origin of the minor bodies of the Solar System.

4. Titan's Energy Balance: General Considerations

The mean flux of solar radiation at Saturn's orbit ($a = 9.538\,84$ AU, $e = 0.055\,65$) is 15.1 W m^{-2}. Titan's albedo is 0.20 for a radius of $R_T = 2850$ km (see Section 7) giving for mean absorbed flux per Titan's unit surface area a value of 3.02 W m^{-2} which corresponds to an equilibrium temperature of $T_{\mathrm{eff}} = 85$ K. (Note for comparison that at $T = 273$ K thermal radiation would carry away 315 W m^{-2}.)

An inspection of Table I shows that the main part of energy released in the detonation of the electrolysis products was expended in ejecting ~ 13% of Titan's original mass. The remaining energy went primarily into heating and melting of the envelope ices. Little energy evidently remains for the heating of water above melting temperature so that part of the material was lost by Titan not immediately in the explosion but rather evaporated from the atmosphere at the expense of the energy of the heated liquid water. Part of the energy which is difficult to evaluate (heat of sublimation, heating above the boiling temperature etc., altogether on the order of $\sim 0.1 \times 10^{29}$ J) was carried away with the ejected material. The loss of the matter into space could conceivably have proceeded at a catastrophic rate as long as the liquid surface temperature was above ~ 273 K and heat flux reached it by convection in the cooling liquid water.

It is thus evident that the cooling time of the water down to the freezing point could have been much shorter than the time of its purely radiative cooling (i.e. < 18 000 yr), and therefore at the present time the water surface may very probably be covered by an ice crust. After the formation of an ice crust the heat flux diminishes rapidly since it is governed by solid state heat conduction, and the surface temperature will begin to drop rapidly. The catastrophic loss of material into space comes to an end.

5. Energetics of Titan with an Ice Crust

If there is an ice crust, evaluation of the outward heat flux from Titan becomes much simpler. Indeed, the thermodynamic parameters of ice and its thermal transport properties are *a priori* much better defined than the characteristics of the atmosphere, and the thermal resistance of a sufficiently thick ice crust should exceed that of a convective atmosphere.

The thermal resistance ratio is characterized by the ratio $\Delta T_{\mathrm{ice}}/\Delta T_{\mathrm{atm}}$ of the temperature drops setting in the crust and the atmosphere. Within an accuracy of a few degrees one may accept for Titan $T_{\mathrm{eff}} \approx 85$ K. The temperature of the lowest atmosphere level for which measurements could be carried out is 92 K (Beatty, 1981), and if the surface lies close to this level, then $\Delta T_{\mathrm{atm}} = 6$ K which is much less than $\Delta T_{\mathrm{ice}} \approx 273 - 92\,\mathrm{K} = 181$ K. Even if we increase ΔT_{atm} by an order of magnitude the heat loss from Titan will still be determined by the properties of its ice crust.

If Titan's surface is an ice crust on liquid water, then the heat flux is due to latent heat of water freezing. Mathematically, the growth of an ice crust represents the well known Stefan's problem (Carslaw and Jaeger, 1959; Pounder, 1965; Hobbs, 1974).

With temperature independent ice parameters, and neglecting the energy stored in the ice proper, the crust thickness may be roughly estimated as

$$\delta = (2K\Delta T_{\mathrm{ice}}t/\rho L)^{1/2},$$

where t stands for the time, $L = 333.5\,\mathrm{kJ\,kg^{-1}}$ the latent heat of melting, K the thermal conductivity, $\rho = 920\,\mathrm{kg\,m^{-3}}$ the ice density.

Compared with standard situations encountered on Earth, here the problem is, however, complicated by two factors: (1) the crust thickness and ΔT_{ice} are so large as to make the heat stored in ice comparable with L, and (2) one should take into account the temperature dependence of c_p and of the thermal conductivity of ice. The latter can be written as (Pounder, 1965; Hobbs, 1974):

$$c_p = 0.00780\,T - 0.0134\,\mathrm{kJ/kg \cdot K},$$
$$K = \frac{488.2}{T} + 0.4685\,\mathrm{W/m \cdot K};$$

and within an accuracy sufficient for our purposes represented in the form

$$c_p = 0.00776T; \qquad K = 611.6/T.$$

Then the heat conduction equation for the process

$$\rho c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial Z} K \frac{\partial T}{\partial Z} = 0$$

will acquire the form

$$C \frac{\partial T}{\partial t} - \frac{1}{T} \frac{\partial}{\partial Z} \frac{1}{T} \frac{\partial T}{\partial Z} = 0.$$

This nonlinear equation with $C = \text{const}$ may be reduced to the heat transport equation with constant coefficients by scaling $\mathrm{d}x = T\mathrm{d}z$. Standard initial and boundary conditions are assumed (see the above references).

The results of ice crust thickness calculations for some characteristic time intervals elapsed from the beginning of water freezing are presented in Table II for different surface temperatures. Also given are the corresponding thermal fluxes q through the surface (because of the difference between R_{surf} and R_{eff} the radiated excess thermal flux will be $\sim 20\%$ less than the value listed in Table II).

The process of ice crust growth and Titan's thermal flux variation in time after the ice explosion and water envelope cooling down to the freezing temperature (~ 273 K) is shown schematically in Figure 1 (data of Reynolds and Cassen, 1979, are also included). There are three phases clearly separated in time: (1) heat loss through ice conduction lasts 10^4–10^6 yr until the crust has become $\delta_c \approx 1$–10 km thick; (2) after this, the energy is removed by convective motion, the energy flux being stabilized at a level of $q_c \sim 0.1$–$0.5\,\mathrm{W\,m^{-2}}$ (because of a large uncertainly in the rheological properties of ice, only an order-of-magnitude estimate can be made of δ_c and of the convective heat flux); (3) after the solidification of all liquid water in $\sim 10^8$ yr the thermal flux transported by ice convection drops drastically down to $\sim 0.01\,\mathrm{W\,m^{-2}}$, (Reynolds and Cassen, 1979) it being sustained now only by the energy of radioactive fission in the rocks of the core. A similar sequence of events had taken place also at earlier stages of development of Titan and of other icy moonlike bodies immediately after their formation.

6. On the Role of Impurities

The above estimates will clearly be valid only provided the role of other compounds making up the ices is minor. As follows from general cosmogonic considerations, from the relatively high abundance of carbonaceous molecules and radicals in the gases of the

TABLE II

Ice crust thickness δ and thermal flux q through the crust vs age t and surface temperature T_{surf}

T_{surf} (K)	T_{ice} (K)	δ(m)			q (W m^{-2})		
		3000 yr	6000 yr	12 000 yr	3000 yr	6000 yr	12 000 yr
85	188	710	1010	1430	1.10	0.78	0.55
100	173	650	920	1300	1.04	0.74	0.52
120	153	580	820	1160	0.95	0.68	0.48

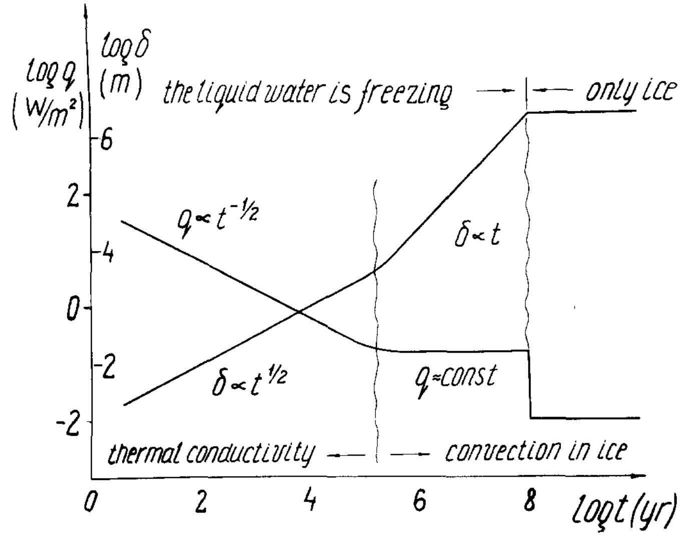

Fig. 1. Thermal flux q and ice crust thickness δ vs time for a moonlike rocky-core icy body (Titan) after the cooling of its water envelope down to freezing temperature (the surface is assumed to be free of hydrocarbons and other compounds).

comets (the carbon-containing molecules are one or two orders of magnitude less abundant than H, O, and OH while the nitrogen-containing ones may be still less abundant by an order of magnitude (Delsemme, 1972)) which, as pointed out earlier, may be fragments of the ice envelopes of moonlike bodies, including Titan, as well as from the very presence of methane in Titan's atmosphere – hydrocarbons such as oil, paraffin, bitumens etc. may constitute a second-major component after water. Some of them are lighter than water and thus should rise to the surface. Their fraction can hardly be 10%; it is probably $\lesssim 1\%$ or even $\lesssim 0.1\%$ (the carbon content in meteorites is as high as 5%, but only $\sim 5\%$ of these 5% are saturated hydrocarbons with $\rho < 1\ \mathrm{g\,cm^{-3}}$ (Sears, 1978); the carbon-containing molecules in the cometary gases are predominantly CN, C_2, C_3, and CO^+; CH is much less abundant while CH_4 and more complex hydrocarbons have not been detected at all). But even in the latter case, the thickness of a 'paraffin' layer on water could be ~ 1 km, i.e. it may be comparable with the possible thickness of the present day ice crust (see Table II).

The thermal conductivity of solid hydrocarbons is an order of magnitude less than that of ice (for paraffin, $K = 0.25\,\mathrm{W/m\cdot}K$, the latent heat of melting $L \approx 150\,\mathrm{J/g}$ at $T \approx 280\,\mathrm{K}$ is onehalf that of ice). Therefore a hydrocarbons layer may affect drastically the process of ice crust growth. The solidification of a liquid hydrocarbon layer of a given thickness should occur much faster than that of the same layer of water since the hydrocarbon ices are heavier than the liquid phase and thus will drown, convection in the liquid providing an efficient heat transport. With a solid hydrocarbon layer $\delta = 1$ km thick floating on liquid water the heat flux will be $q \approx K\Delta T/\delta = 0.25 \times 200/10^3 = 0.05\,\mathrm{W\,m^{-2}}$ which is an order of magnitude less than that for pure water (see Table I and Figure 1). Even with a solid upper water layer under such a hydrocarbon crust, hydrocarbons will provide a major contribution to thermal resistance with the process lasting $\sim 10^4$ yr.

Therefore if measurement yield for q a value markedly lower than these in Table I this will indicate the existence of a solid hydrocarbon crust, the actual magnitude of q providing a possibility of estimating the thickness of this crust provided convection has not set in in it ($\delta \approx K\Delta T/q$).

The possibility of incomplete solidification of the hydrocarbon mixture (a peculiar 'soup' of heavy frozen and light liquid hydrocarbons) and the presence of convection lead to an increase of q above the $0.05\,\mathrm{W\,m^{-2}}$ level.

7. The IR Observations of Titan

To detect from space the excess radiation from Titan, two quantities should be compared: the amount of radiated energy and the amount of absorbed solar energy.

The latter quantity depends on the magnitude of Bond albedo A. The most detailed study for Titan was carried out by Younkin (1974) who used for this purpose his own narrow-band measurements in the range $0.5 \leqslant \lambda \leqslant 1.08\,\mu\mathrm{m}$ as well as medium bandwidth measurements for $0.3 \leqslant \lambda \leqslant 0.5\,\mu\mathrm{m}$ of McCord *et al.* (1971), and an extrapolation up to $\lambda = 4\,\mu\mathrm{m}$ basing on analogies with the spectral features of Jupiter and Saturn. The range $0.3 \leqslant \lambda \leqslant 4\,\mu\mathrm{m}$ encompasses 98% of the solar radiation flux.

Younkin obtained $A/\bar{q} = 0.21$, where $\bar{q}$ is the phase integral, for $R_{\mathrm{Tit}} = 2425$ km. According to the data derived for Earth ($\bar{q} = 1.05$), Venus ($\bar{q} = 1.2$), Mars ($\bar{q} = 1.02$) (Allen, 1977) and for various particle scattering functions, this integral should be $\bar{q} = 1.1$–1.5 (for the giant planets, $\bar{q} = 1.6$ (Allen, 1977)). Younkin assumed $\bar{q} = 1.3$ whence $A = 0.27$ ($\pm$ 0.04). For the radius derived by Smith (1980) from the Pioneer data ($R = 2850$ km), $A = 0.20$ ($\pm$ 0.03). Then for the equilibrium temperature taking into account solar irradiation we will obtain $T = 85$ K.

The most probable value for Titan's excess thermal flux, as follows from the preceding section, should lie in the range ~ 0.5–$0.05\,\mathrm{W\,m^{-2}}$ thus constituting ~ 15 to $\sim 1.5\%$ of the absorbed solar flux ($\sim 3.02\,\mathrm{W\,m^{-2}}$). This corresponds to an increase of T_{eff} by ~ 3.5–0.4% which will raise the equilibrium temperature (≈ 85 K) only by 3–0.3 K. Thermal radiation at $T \approx 85$ K lies mainly within $7 \lesssim \lambda \lesssim 300\,\mu\mathrm{m}$.

There are available at present quite reliable measurements in the range 7 to 35 μm

(Gillet *et al.*, 1973; Morrison *et al.*, 1972; Low and Rieke, 1974; Gillet, 1975; McCarthy *et al.*, 1980). Using these data, McCarthy *et al.* (1980) concluded that the radiated energy exceeds by a factor 1.1 ± 0.1 the absorbed flux (for $A = 0.2$ and $R = 2916$ km). It was assumed that $T_B = 75$ K at $\lambda > 30\,\mu$m. The fraction of the energy radiated away in the extrapolated regions ($\lambda > 30\,\mu$m) constitutes 65%.

Froidevaux and Ingersoll (1980), basing on 30 measurements of Pioneer 11 at $\lambda = 45\,\mu$m, obtained $T_B = 75 \pm 5$ K (for $R = 2800 \pm 100$ km).

Recent airborne measurements in four broad passbands between 35 and 150 μm by Loewenstein *et al.* (1980) showed the spectrum between 38 and 107 μm to be apparently isothermal with $T_B = 76 \pm 3$ K (for $R = 2700$ km). Their integration of the energy in the range covered by the experiment (5 to 150 μm) yielded $T_{eff} = 86 \pm 3$ K (for $R = 2800$ km) which, within the accuracy of measurements, corresponds to the flux absorbed from the Sun.

Thus there are as yet no observational data supporting the presence of excess radiation from Titan.

One can, however, make the following recommendations:

(1) It would be desirable to extend measurements into the range $\lambda > 150\,\mu$m as well as to repeat observations at the maximum of thermal radiation, 30–100 μm to improve statistics and reduce errors.

(2) Note that all the above measurements were carried out starting with 1972, i.e., during the epoch of Saturn's being at perihelion (February, 1974). When at perihelion, Saturn's system receives 25% more solar energy than at aphelion. This possibly could account for the short wavelength ($\lambda \lesssim 20\,\mu$m) data of Low and Rieke (1974) being systematically somewhat higher than those of McCarthy *et al.* (1980) obtained in January, 1978. The thermal inertia of Titan's atmosphere is characterized by a time of $\sim 10^{10}$ s (Golitsyn, 1979) which is much larger than the orbital period ($\sim 10^9$ s). Only the upper atmospheric layers responsible for the short wavelength radiation can respond to orbital variations of the solar flux. Therefore any study of Titan's energy balance should take into account the variability of the radiation flux, thermal inertia and possible mixing of the atmosphere. Part of the energy is possibly still being expended in the loss of atmospheric gases into space.

(3) More accurate measurements of Titan's albedo known at present only to within $\sim 15\%$ (see above) are obviously needed.

8. A Possible Origin of Saturn's Excess Radiation

Practically all the observed features of Saturn's system and of the associated bodies can be explained within the hypothesis of an historically recent ($\sim 10^4$ yr ago) explosion of Titan's ices. It would be only natural to consider also from the same standpoint the possibility of excitation of Saturn's excess luminosity which is about $\sim 10^{17}$ W.

As a result of the explosion, Titan lost, as already mentioned (see Table I), $\Delta M \sim 2 \times 10^{25}$ g of its mass. Its major part and, in particular, the nonexploded fragments of the outermost ice layers were ejected beyond the bounds of Saturn's system by Titan's perturbations. The fragments became cometary nuclei (Paper 1).

If a small part of the material ejected from Titan, say 1%, fell on Saturn, the liberated energy ($\sim 1.25 \times 10^{29}$ J) would be sufficient to sustain the observed excess in luminosity for $\sim 40\,000$ yr.

Initially the accretion of Titan's material proceeded obviously at a higher rate, its major part having fallen on Saturn practically immediately after the explosion. The thermal inertia of Saturn's outer layers, say down to a depth of ~ 300 km where the pressure reaches $p \approx 300$ atm (e.g., Zharkov *et al.*, 1974) is, in principle, sufficiently large; indeed, according to Golitsyn (1979) it is equal to

$$t_{\text{th}} = c_p p / g \sigma T_{\text{eff}}^3 \approx 20\,000 \text{ yr};$$

where $c_p = 0.013$ J/kg$\cdot K$ is the heat capacity, $g = 11$ m s^{-2} the gravitational acceleration, σ Stefan's radiation constant, $T_{\text{eff}} = 95$ K the effective temperature. Therefore, one could restrict oneself to an assumption that Saturn is still radiating the energy released on it $\sim 10^4$ yr ago. We note, however, with interest that the continuing accretion of material ejected by Titan in the past can account, in principle, for the present day energetics of Saturn.

Part of this material including water vapor and smaller (km-size) fragments remained inside Titan's orbit. Closer to Saturn the conditions were such as to allow the water to reach the triple point ($T \sim 273$ K) with the products of condensation coalescing into large (1–10 cm) particles of ice. This is how the easily observable inner rings of Saturn formed. Their optical properties are determined by the above mentioned ice particles, and the dynamics and energetics, by the km-size ice fragments representing the second population of the rings in which most of the mass is contained.

Basing on the Pioneer 11 data, Anderson *et al.* (1980) estimate the mass of the rings at present to be $m_r \lesssim 3 \times 10^{-6} M_{♄} = 1.7 \times 10^{24}$ g, i.e. $\lesssim 10\%$ of the mass lost by Titan.

The ring decay time Δt due to the effective viscosity caused by the particle collisions is related to the thickness of the rings as (see, e.g., Goldreich and Tremaine, 1978)

$$Z_0^2 t \leqslant (\Delta r^2/\Omega)(\tau + \tau^{-1}) \approx 10^6 \text{ km}^2 \text{ yr},$$

where Δr ($\approx 60\,000$ km) is the ring width, Ω ($\approx 2 \times 10^{-4}$ s^{-1}) the orbital angular velocity, τ (≈ 1) the optical thickness. Similar estimates have been obtained by other authors (Bobrov, 1970; Trulsen, 1972; Cuzzi *et al.*, 1979; see also Paper 1).

Observations performed during Earth's transit through the ring plane yield $Z_0 = 0.5$–1.5 km (e.g., Bobrov, 1970). Hence $t \lesssim 0.4$–4 million yr, with the present day accretion of ring particles resulting in an energy release of $\sim (0.1–1) \times 10^{17}$ W which agrees satisfactorily with Saturn's excess luminosity.

9. Conclusions

In the foregoing we have started from the assumption of a recent (3.5–10 thousand yr ago) explosion of Titan's ice electrolysis products. This assumption provides a common explanation for many peculiar features of Saturn's system and offers a new approach to the problem of origin of the minor bodies in the Solar System. We have succeeded also in pointing out a new source for Saturn's excess luminosity. One cannot *a priori* exclude the possibility of similar reasons accounting totally or partially for the excess luminosity of Jupiter and Neptune.

Detection of an excess thermal flux from Titan would be that experimentum crucis which would convince us of the reality of a recent explosion of Titan's ices. The predicted excess flux is 0.5–0.05 $\mathrm{W\,m^{-2}}$ which may be compared with $\sim 3\,\mathrm{W\,m^{-2}}$ which Titan should emit in the IR range only as a result of absorbed solar radiation. The upper bound ($0.5\,\mathrm{W\,m^{-2}}$) is just at the limit of present day precision in the measurement of Titan's energy balance ($\sim \pm 15\%$) and effective temperature (± 3 K, Loewenstein *et al.*, 1980). This demonstrates the importance of continuing the measurement in order to obtain more accurate information on Titan's albedo and IR flux. Of particular importance are observation from spaceprobes which could yield a more accurate value of the phase integral $\bar{q}$ and reveal possible photometric irregularities in latitude. Series of measurements are needed to reveal seasonal variations whose existence and role are completely unknown, particularly in view of the large thermal inertia of the atmosphere.

One cannot at present exclude the possibility of the atmosphere being so thick and opaque that it extends from the level where Voyager 1 measured $T \approx 93$ K and $p \approx 1.6$ atm still deeper down by 40 km where $T \approx 273$ K and $p \approx 70$ atm, and where liquid water may exist on the surface.

This assumption, however, should be regarded as hardly probable for two reasons at least. First, the thermal resistance of such convective atmosphere cannot be so high as to reduce the energy flux by almost three orders of magnitude (from $\sim 300\,\mathrm{W\,m^{-2}}$ down to $\sim 0.5\,\mathrm{W\,m^{-2}}$). Second, a consideration of the energy balance of Titan's ices explosion (Table I), despite possible inaccuracies in estimates of major quantities involved, leads one to a general impression that Titan has been losing material efficiently for some time after the explosion as a result of the water giving off its energy until the beginning of freezing. Thus the atmosphere including water vapor and suspended ice crystals was unstable, and was escaping from Titan at a high rate at least as long as its lower layers were in contact with the liquid water and hence were warm.

The lower limit ($\sim 0.05\,\mathrm{W\,m^{-2}}$) of Titan's excess thermal flux is equal to mean energy flux through the Earth's crust and is three times that from the Moon's interior. It is too low to leave us hope of detecting and measuring it in the Earth-based or spaceborne experiments in the foreseeable future. Just as in the case of the Moon, such a flux could apparently be detected only by directly measuring the temperature gradients in Titan's crust from a probe landed on its surface. Such a probe would yield unambiguous answer concerning the properties and composition of the surface (liquid vs solid, water vs hydrocarbons), as well as measure by seismic, acoustic and radar sounding the thickness and structure of the crust. One cannot exclude the possibility of the crust having a layered structure as a result of ejection of the liquid phase through fissures in the comparatively thin ($\lesssim$ 1 km) crust. These ejections could account for the variability of Titan mentioned by some authors (Anderson, 1977).

A comparison of such data with similar data obtained, say, for Callisto which did not undergo explosions (Paper 2) would reveal uniqueness of Titan's structure in that it still has a deep ($\sim$ 1000 km) ocean of liquid water under a fairly thin ice crust. It should be noted that the existence of global multiring concentric structures on Callisto's surface, irrespective of their origin (be it meteoric (Smith *et al.*, 1979) or convective (Paper 2)), is a point in favor of a very thick ($\sim 10^3$ km), most probably solidly frozen ice envelope on Callisto.

Indeed, a convective origin assumes the horizontal and vertical size of the cell to be comparable.

If, however, these structures result from collisions with large meteorites, then in the case of thin ($\sim 10^2$ km) ice crust the splashing out and subsequent mixing of the water caused by such an impact would have resulted in elimination of any traces of the possible initial concentric symmetry.

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