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TITAN'S LATITUDINAL TEMPERATURE DISTRIBUTION AND SEASONAL CYCLE

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Abstract. Voyager IRIS brightness temperature measurements of Titan at a wavelength of 530 cm^{-1} are crudely indicative of ground or lower tropospheric temperatures and indicate 93 K for the equator and 91 K for both northern and southern high latitudes. The symmetry between north and south is unexpected for the time of Voyager encounter (Northern Titan spring). We show that this near-symmetry can arise naturally in a model where the poles are ''pinned'' year-round at the dew point of CH_4-N_2 lakes or, more probably, a CH_4-N_2 rich surface layer on a deep ethane-rich ocean. For a polar temperature of 91 K, the model implies that the atmosphere contains somewhat less than 8% mole fraction of CH_4.

Introduction

Voyager 1 observations established that Titan's atmosphere is predominantly N_2 with a surface temperature of about 94 K, and a surface pressure of 1.5 bars [see review by Hunten et al., 1984]. Methane is the predominant hydrocarbon above the tropopause cold trap and must be continuously resupplied from below because it is rapidly photolyzed, primarily to ethane and acetylene. The CH_4 abundance in the lower troposphere is not known, but could be ~5% mole fraction. The near surface temperature gradient in equatorial regions is indistinguishable from the lapse rate of a dry N_2 atmosphere [Lindal et al., 1983] implying that at least in equatorial regions, there is no near-surface condensation and no predominantly methane ocean [Flasar, 1983; Eshleman et al., 1983]. The simultaneous requirements of a methane source, ethane sink, and ''dry'' surface are all satisfied by an ethane-rich ocean [Lunine et al., 1983].

Latitudinal atmospheric structure on Titan is constrained only by infrared observations [Flasar et al., 1981], and the brightness temperature data for the spectral region centered on 530 cm^{-1}, reproduced in Figure 1, are believed to be close to actual surface temperatures, except for a small systematic reduction ~1 K. The data indicate a small but significant (2-3 K) temperature difference between equator and pole. This is independent evidence for a ''dry'' surface since if global condensation of the atmosphere were occurring, then an intolerably large equator to pole pressure difference would arise due to the strong dependence of vapor pressure on temperature. The ethane-rich ocean behaves like a ''dry'' surface because the condensate in equilibrium with it must necessarily contain large amounts of ethane. This is unavailable because of ethane's extreme involatility (the atmosphere contains $\lesssim$1 mm precipitable C_2H_6, with a latent heat content equivalent to only ~10^5 secs insolation). Large scale condensation of the atmosphere can only occur if the temperature is low enough to allow condensation of a phase containing only CH_4 and N_2; under Titan conditions this phase would be a liquid [Omar et al., 1962] and might form in polar regions. Solid or liquid pure methane is impossible on Titan.

Our focus here is on the near-symmetry of the temperature distribution about the equator. If an asymmetry is present, it is in the direction of higher temperatures in the Southern Hemisphere. It is most significant, however, that the Northern and Southern high latitudes have indistinguishable temperatures, a surprising behavior for the equinox conditions of the Voyager encounter (Northern spring), especially for an atmosphere in which the radiative time constant exceeds the Titan ''year'' (29.5 years) by a factor of ~4. If Titan were dominated by radiative balance and atmospheric energy storage, then the observed seasonal cycle would lag the insolation by almost a full season and the maximum temperature difference between hemispheres (or poles) would have occurred at the time of Voyager encounter. However, latitudinal heat transport, presumably by meridional circulation, must be present to reduce the observed equator-pole temperature difference from the value predicted by a purely radiative state (~15 K) to the observed value of 2-3 K; this is discussed by Flasar et al. [1981] and further by Flasar in Hunten et al. [1984]. It is less obvious whether this circulation could also eliminate the extreme hemispheric asymmetry predicted by the radiative model. In the next section, we present simple models which suggest that the asymmetry might persist despite latitudinal heat transport. Asymmetries in albedo exist [Sromovsky et al., 1981] and might reduce the predicted temperature asymmetry, but we find that this effect is too small. Since we dislike coincidental symmetries, we sought to identify a likely physical process which might enforce symmetry. ''Pinning'' the poles at the atmosphere dew point is shown to be quantitatively successful as well as physically appealing.

Simple Models

We considered the following energy balance equation for a unit vertical column of atmosphere:

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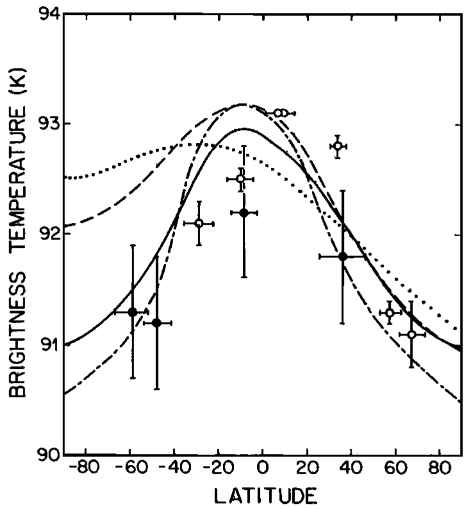

Fig. 1. Titan brightness temperatures at 530 cm^{-1} as a function of latitude (positive means Northern hemisphere). Voyager data points (open circles = days; filled circles = night) are compared with four theoretical models for vernal equinox.

. . . . . No latent heat effects, constant albedo, n = 1, k = 8 x 10^{12} cgs.

– – – – – No latent heat effects, A = 0.2 ± a cos ωt (– ≡ northern hemisphere, + ≡ southern hemisphere, ω ≡ 2π/(29.5 years), t = time measured from Vernal equinox, a = 0.18 at poles, 0.15 at mid-latitudes), n = 1, k = 3.6 x 10^{12} cgs.

– . – . – Poles pinned at 90.5 K, constant albedo, n = 1, k = 2 x 10^{12} cgs.

———— Poles pinned at 91 K, A = 0.2 ± a cos ωt (same notation as above: a = 0.08 at mid-latitudes, polar value does not affect the models), n = 1, k = 2.8 x 10^{12} cgs.

$$\gamma \rho_g C_p H \frac{\partial T}{\partial t} = (1 - A) S(\theta,t) - \sigma T^4$$

$$+ L\dot{\Sigma} + \frac{Hk}{R \sin\theta} \frac{\partial}{\partial\theta} (\sin\theta \, |\beta|^{n-1} \beta)$$

$$\beta \equiv \frac{1}{R} \frac{\partial T}{\partial \theta} \qquad (1)$$

where ρ_g = gas density, C_p = specific heat, H = atmospheric scaleheight, γ is a numerical constant slightly in excess of unity, T = effective temperature (assumed to be related to the ground temperature by the equation $T_{ground} \simeq 1.1$ T), t is time, S(θ,t) is the diurnally averaged insolation appropriate to Titan's obliquity of 26.7° assuming Titan's rotation axis is normal to its orbit about Saturn, A represents the Bond albedo (but see below) and may also be a function of time or position, θ is the colatitude (θ = 0 at the north pole, θ = π at the south pole), σ is Stefan-Boltzmann's constant, L is the latent heat of condensation for the CH_4–N_2 liquid which coexists with the atmosphere and $\dot{\Sigma}$ is the downward mass flux per unit area (positive for condensation, negative for evaporation), k is an empirical heat transfer coefficient, β is the latitudinal temperature gradient (R is Titan's radius), and n is an exponent to be specified (1 ≲ n ≲ 2). Since we have related the surface and effective temperatures in a crude way and are making no attempt to keep track of where the insolation is absorbed, the parameter A should be regarded as an adjustable parameter, chosen to reproduce the correct average surface temperature. The amplitude and asymmetry of the seasonal cycle was found to be insensitive to the choice of A. Equation (1) also omits gound storage of sensible heat; we modeled this and found it to be negligible. We have chosen to model latitudinal heat transport by a ''local'' (eddy) term alone; if n = 1 then k can be identified as an eddy thermal conductivity. If n = 3/2 then our prescription has the form of ''mixing length'' convection. We do not pretend that this is an adequate description of the physical process; rather, we adopt the pragmatic viewpoint that if a model such as this is incapable of explaining the symmetry of the temperature distribution, then there is little reason to suppose that a ''sophisticated'' model will do better (except by fortuitous coincidence). Although first principles models of meridional circulation exist, they have had rather limited success for either Titan or Venus, the body most analogous to Titan [see Flasar's discussion in Hunten et al., 1984].

Approximate analytical solutions to equation (1) exists for small temperature fluctuations, negligible latent heat effects and n = 1, but they are complicated because the expansion of S(θ,t) in Legendre polynomials of θ, and frequency harmonics requires many terms, especially in polar regions. We concentrated on numerical solutions and divided Titan into five zones of equal surface area (two polar regions, two mid-latitude zones, and an equatorial belt). Numerous numerical integrations were performed for various values of k and for n = 1 or 2; the integration was truncated after transients had decayed and a repeating seasonal cycle was achieved. Some of these models are shown in Figure 1. When k = 0, the equator to pole difference is very large (between 10 and 15° K), far too large to be included in the temperature range shown on Figure 1, demonstrating that latitudinal heat transport is essential. When there is no latent heat term, models with fnite k always give unacceptably large asymmetries between Northern and Southern hemispheres. The dotted line in Figure 1 shows one of the better models, still an unacceptable fit to the data despite the extreme flexibility of the model. Models with n = 2 exhibited very similar behavior to models with n = 1. Ground-based and IR data suggest a seasonally-modulated albedo asymmetry [Sromovsky et al., 1981] so we ran several models to test the effect of this. Extremely large albedo variations were found to produce only modest changes in the temperature distribution and failed to eliminate the N-S asymmetry. The dashed line in Figure 1 corresponds to an almost 100% seasonal modulation of the albedo. In retrospect, the insensitivity is hardly surprising: one would need to allow the albedo to approach unity in some regions to produce significant effects, given the smoothing effects of latitudinal heat transport.

We assessed the effect of condensation and

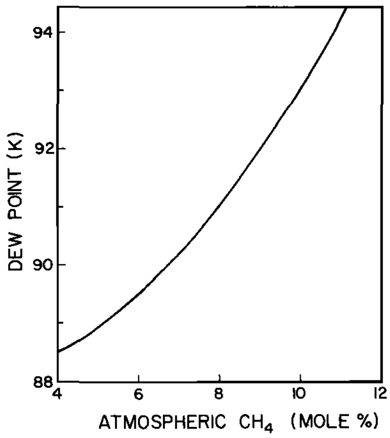

Figure 2. Dew point for a 1.5 bar atmosphere, composed entirely of N_2 and CH_4, as a function of CH_4 mole fraction. Curve is based on theoretical modeling of data and has an uncertainty ~0.5 K at fixed CH_4 fraction.

evaporation, simply by demanding that the two polar regions remain at the same temperature at all times, but setting $\dot{\Sigma} = 0$ for all other latitudes. Equation (1) is then simply a means of solving for $\dot{\Sigma}$ in the polar regions. This crude model is self-consistent because the temperature in the other zones never drop to the polar temperature. The dot-dashed and solid lines in Figure 1 correspond to models of this type and provide a better (but by no means perfect) fit to the data. A reasonable estimate for the polar temperature is ~91 K.

We can relate this to the composition of the atmosphere if we assume: (i) Only CH_4 and N_2 condenses; (ii) The atmosphere is everywhere at 1.5 bars and is almost entirely N_2 and CH_4; (iii) No supersaturation occurs; (iv) The pole is at the dew point of the atmosphere; (v) The atmosphere is in thermodynamic equilibrium with the surface. (For the meteorological reasons discussed by Flasar [1983], this is unlikely to be exactly correct.) Using data for the CH_4N_2 system [Cheung and Wang, 1964], we constructed slightly non-ideal Henry's laws [cf. Lunine and Stevenson, 1985] leading to the dew point estimates shown in Figure 2. These suggest an atmospheric CH_4 mole fraction ~8%. This may be an overestimate by as much as a factor of two if one allows for the possibility that the lowermost polar troposphere lies on a wet adiabat and is in mild disequilibrium with the surface.

The Condensation-Evaporation Cycle

With $L \sim 10^9$ erg/g, less than ten meters of liquid must condense at the pole during winter to keep the temperature from dropping lower than ~91 K; a similar amount evaporates during polar summer. This is easy to envisage on a body with a truly dry surface, but we concentrate here on the seasonal cycle for the more likely case of a Titan covered by an ethane-rich ocean. For the proposed cycle to work, we must demonstrate that (a) a nitrogen-methane rich surface layer can form on an ethane rich ocean; and (b) latent heat effects are important only near the pole. The former is partly guaranteed by laboratory studies [Chang and Lu, 1967] which show that the C_2H_6-CH_4N_2 mixture becomes less dense as CH_4 and N_2 are added in vapor equilibrium. However, we must also understand near surface diffusion.

Consider a well-mixed C_2H_6-CH_4-N_2 ocean coexisting with Titan's atmosphere, initially at 94 K, and then allow the temperature to decrease, meanwhile maintaining the atmosphere at constant pressure and composition. The phase diagram [Lunine and Stevenson, 1985] dictates that the ocean surface layer will become progressively N_2 and CH_4 rich, but to an extent limited by upward C_2H_6 diffusion from the deep ocean (required because the atmosphere is an insignificant source of C_2H_6). Provided the temperature is still $\gtrsim 1$ K in excess of the dew point for N_2-CH_4, solution of the diffusion equation gives a mass flux from condensation

$$\dot{\Sigma} \simeq 0.5 \rho (D\omega)^{1/2} \qquad (2)$$

where ρ is the liquid density, D is the interdiffusion coefficient, and $\omega = 2\pi/(29.5 \text{ years})$. If D is dominated by molecular diffusion, then we estimate $D \simeq 2 \times 10^{-5}$ cm^2/s, based on liquid argon data and modeling [March and Tosi, 1976]. If eddy diffusion is relevant, the $D < 10^{-4}$ cm^2/s using scaling laws developed for Earth's oceans [Broecker, 1981]. In either case, Equation (2) predicts that the latent heat flux is $\lesssim 10\%$ of insolation (but becoming much larger if one is within ~1 K of the N_2-CH_4 dew point). This demonstrates the consistency of the model. The stable N_2-CH_4 rich surface layer developed during winter is destabilized by small scale Rayleigh-Taylor instabilities during the summer ocean warm-up.

Concluding Comments

We suggest that Titan has a global or nearly global ethane-rich ocean, with a surface layer ($\lesssim$ few meters in depth) which is enriched in CH_4 and N_2 as one approaches the pole. This al-

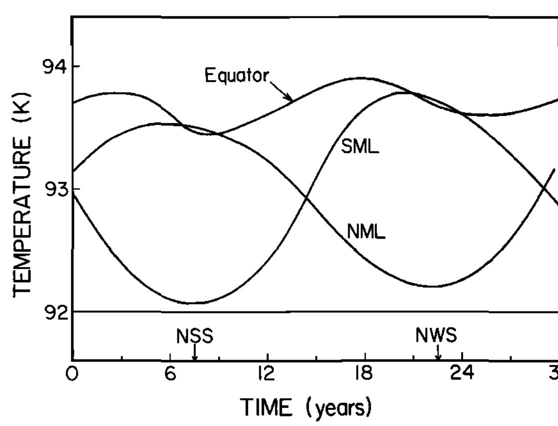

Figure 3. Predicted seasonal cycle for the preferred model (solid line of Fig. 1) with the assumption that physical temperature is 1 K greater than 530 cm^{-1} brightness temperature. Time is measured from Vernal Equinox; NSS = Northern summer solstice, NWS = Northern winter solstice, SML = Southern mid-latitudes, NML = Northern mid-latitude; horizontal line at 92 K represents both poles.

lows direct condensation from the atmosphere and buffers polar temperatures at a temperature close to the dew point of the atmosphere. As a test of the model, polar occultations to detect a ''wet'' lower troposphere would be best; but as a substitute we offer the predicted seasonal cycle in Figure 3.

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