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Nonisothermal Pluto Atmosphere Models

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We calculate the thermal profile of a model Pluto atmosphere containing a substantial number fraction of methane molecules, taking into account the heating of the atmosphere by absorption of solar infrared flux and the cooling by conductive transport to the planet's surface. We assume an equilibrium temperature of the high atmosphere equal to 106°K and an atmospheric composition with an appreciable fraction of molecules heavier than methane (such as, perhaps, CO or N_2). For surface pressures of a few microbars, we find that an appreciable temperature gradient must exist close to the surface. The predicted stellar occultation lightcurve for such a Pluto atmosphere agrees with observations, suggesting that an inferred Pluto haze layer may not exist. Instead, similar effects on the lightcurve could be produced by the strong temperature gradient near the surface. Our alternative model implies that Pluto's solid surface probably lies in the vicinity of 1180 km from the planet's center and that the normal and tangential optical depth of the atmosphere is quite negligible. We calculate an upper limit to the escape rate for the model atmosphere deduced here and find that the minimum time for depletion of the atmospheric methane inventory is about 30 Earth years. © 1990 Academic Press, Inc.

I. INTRODUCTION

The discovery of a Pluto atmosphere by stellar occultation, and the initial interpretations of the data (Elliot *et al.* 1989, Hubbard *et al.* 1988), provided a convincing case for a relatively simple atmosphere composed primarily of methane. The observed atmospheric scale height was consistent with pure methane at a temperature in the range 60–70°K, and this temperature was only some 10–20°K higher than the surface temperature of Pluto inferred from IRAS data (Sykes *et al.* 1987). Moreover, at such a temperature, the vapor pressure of the methane ice known to exist on the surface (Cruikshank *et al.* 1976) would be more than adequate to supply the observed atmosphere. The one feature of the observations which could not be simply explained by this model was the sharp drop in the center of the lightcurve observed by Elliot *et al.* Elliot *et al.* calculated the minimum flux in the occultation shadow of an isothermal atmosphere to be about 0.26 of the unocculted value, whereas they found the observed value to be smaller than 0.01. Their best-fit model for Pluto's occultation shadow is plotted in Fig. 1.

Elliot *et al.* invoked a haze layer to explain the unexpectedly dark center of Pluto's occultation shadow. However, an alternative explanation becomes attractive if we abandon the idea that Pluto's atmosphere is composed primarily of methane. Yelle and Lunine (1989) have shown that Pluto's upper atmosphere will heat to a temperature in excess of 100°K as long as some methane is present. It then follows, from the scale height constraint, that heavier molecules must also be present. By the same token, a temperature gradient must exist. In this paper, we investigate such models and show that they can provide an alternative explanation for the characteristics of Pluto's occultation shadow. We also discuss the implications for the structure and evolution of Pluto's volatiles.

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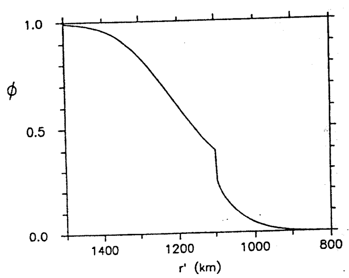

FIG. 1. Pluto occultation model lightcurve (normalized stellar flux ϕ versus radial distance r' from center of shadow), calculated from the parameters of the refraction plus haze layer model given by Elliot *et al.* (1989).

II. MODEL ATMOSPHERES

The model atmospheres presented here are similar to those calculated by Yelle and Lunine (1989), but they have been fine-tuned to better match the occultation data. As Yelle and Lunine discuss, an asymptotic temperature of 106°K is obtained for a wide variety of parameters. This temperature is determined by the properties of the CH_4 molecule and the solar flux incident upon the atmosphere, both of which are well known. However, the temperature gradient near the surface is determined by the competition between radiative cooling rates and thermal conduction and consequently is sensitive to a number of parameters which are uncertain or completely unknown. This gives us some latitude in fitting the occultation data and also allows us to place tighter constraints on the CH_4 mixing ratio.

These model atmospheres neglect some potentially important effects such as diurnal variations in surface temperature, dynamics driven by diurnal or seasonal temperature variations, and aerosol heating. Any or all of these may affect the near-surface temperature gradient. For this reason we have not attempted to find a model atmosphere which precisely matches the occultation light curves but rather simply point out that the temperature gradient must exist and, according to these simple models, should be large enough to produce observable consequences in the light curves.

To our knowledge the thermal conductivities of CH_4, N_2, and CO have not been measured at temperatures relevant to the atmosphere of Pluto. Therefore, we have calculated the thermal conductivities of CH_4, N_2, and CO from the formula given by Hirschfelder *et al.* (1954, p. 534) using the molecular force constants also given by Hirschfelder *et al.* Results for all three molecules are very similar, differing by less than 10% at 100°K. The calculations also agree very well with extrapolation of room temperature CH_4 thermal conductivity measurements through the formula (Gray 1963)

$$\kappa = 5.63T^{1.12} \text{ erg cm}^{-1} \text{ sec}^{-1}.K^{-1} \quad (1)$$

The agreement between these different approaches is reassuring and we adopt this expression for the thermal conductivity of the atmosphere.

The radiative cooling rate is given by

$$L = gn_M h\nu A_R \frac{nZP_{10}}{nZP_{10} + A_R} \exp\left(-\frac{h\nu}{k_B T}\right), \quad (2)$$

where n is the atmospheric number density, n_M is the CH_4 number density, Z is the collision rate, P_{10} is the probability that a V–T transition will occur during a collision, A_R is the radiative decay rate, $h\nu$ is the photon energy, g is the ratio of statistical weights for the upper and lower vibrational levels, k_B is Boltzmann's constant, and $k_B T$ is the thermal energy. Measurements of P_{10} at low temperatures are not available; therefore, we have extrapolated room temperature measurements assuming the standard Landau–Teller temperature dependence (cf. Lambert 1977).

$$P_{10}(T) = P_0 \exp(-A_0/T^{1/3}), \quad (3)$$

where we have taken the constant, A_0 = 35°K$^{1/3}$ following Lellouch *et al.* (1990). Values for P_{10} at room temperature are 5.3 × 10^{-5}, 9.4 × 10^{-6}, and 5.5 × 10^{-6}, for CH_4–CH_4, CH_4–CO, and CH_4–N_2 collisions, respectively (Yardley *et al.* 1970).

The radiative cooling rate depends directly on the methane mixing ratio and the collisional deactivation rate, P_{10}. As either quantity is increased the temperature gradient becomes steeper. Examples of this effect are shown in Fig. 2. As we discuss below, analysis of the occultation light curves suggests that the temperature gradient must be on the order of 10 K°/km to explain the data without the assumption of a dust layer. Gradients this large are only achieved with CH_4 mixing ratios close to 50%. If an extreme value of $P_{10} = 1 \times 10^{-4}$ (at room temperature) is used, CH_4 mole fractions as small as 10% may produce an acceptably steep temperature gradient. Larger values of P_{10} have little effect because the product nZP_{10} becomes greater than A_R. Of course, still larger temperature gradients may be achieved with larger CH_4 abundances but this would be inconsistent with the scale height measured in the isothermal region of the atmosphere (Yelle and Lunine 1989). We conclude that if the temperature gradient interpretation of the occultation data is correct the CH_4 mole fraction must be ~10–50% near the base of the Pluto atmosphere.

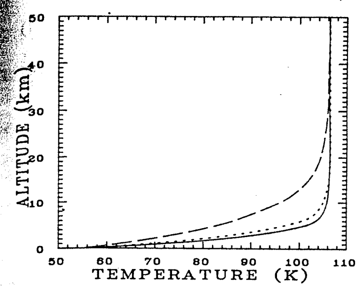

FIG. 2. Results of thermal structure calculations for several models. The solid line shows the temperature profile obtained with a methane mole fraction of 50% and a collisional deactivation probability of $P_{10} = 3 \times 10^{-5}$ at room temperature. The long dashed curve represents results for a methane mole fraction of 10% and $P_{10} = 3 \times 10^{-5}$. The short dashed curve shows results for a methane mole fraction of 10% and $P_{10} = 1 \times 10^{-4}$. Both the solid line and short dashed line display temperature gradients close to that required to explain the occultation light curves.

III. OCCULTATION THEORY

A. The Direct Problem

Theories for the shape of the lightcurve of an isothermal Pluto atmosphere have been derived by Hubbard *et al.* (1988) and Elliot *et al.* (1989). In this section we obtain a generalization of these theories for the case where the atmosphere becomes isothermal at a temperature T_I for all radii $r > r_I$, but where the atmospheric temperature $T = T(r)$ for $r < r_I$, where r_I is a radius which lies substantially above the region where the temperature deviates from T_I. We shall assume that r_I = 1214 km, and T_I = 106°K. Define the function

$$f(r) = T(r)/T_I, \quad (4)$$

and let

$$\lambda_I = \frac{GMm}{r_I k_B T_I}, \quad (5)$$

where G is the gravitational constant, M is Pluto's mass, and m is the number-averaged mass of an atmospheric molecule. We let λ_I = 19.7, which corresponds to an average molecular mass of about 25 amu for T_I = 106°K, consistent with the occultation-derived scale height of the upper atmosphere. For a mixture of CH_4 and CO or N_2, this would correspond to a methane mole fraction of about 0.2.

Using the equation of hydrostatic equilibrium, we then have for the pressure

$$P(r) = P_I e^{-\lambda_I \eta(r)}, \quad (6)$$

where

$$\eta(r) = \int_{r_I}^{r} \frac{r_I dr}{r^2 f}, \quad (7)$$

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$$\Phi = \Phi_0(r) \quad (r > r_I),$$

$$\Phi = \Phi_0(r) + \Delta\Phi(r) \quad (r < r_I), \quad (8)$$

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$$) = 2kN_I \int_r^{r_I} \frac{y dy}{\sqrt{y^2 - r^2}} \left[\frac{e^{-\lambda_I \eta}}{f} - e^{-\lambda_I(1-r_I/y)}\right], \quad (9)$$

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$$D\alpha = r - r', \quad (10)$$

ere D is the distance from the planet to
observer. From conservation of energy,

$$\frac{1}{2}(r^2 - r'^2) = \int_{r'}^{\infty} y dy[1 - \phi(y)], \quad (11)$$

and thus we obtain $\alpha(r)$. Then, by an Abel transform, we have

$$N(r) = \frac{1}{\pi} \int_r^{\infty} \frac{\alpha(y) dy}{\sqrt{y^2 - r^2}}. \quad (12)$$

IV. COMPARISON WITH STELLAR OCCULTATION DATA

The Pluto occultation lightcurve observed by Hubbard *et al.* (1988) did not penetrate below a flux level $\phi = 0.45$, and the data are consistent with an isothermal atmosphere with $\lambda \approx 20$. The lightcurve observed by Elliot *et al.* (1989) shows similar behavior for $\phi > 0.43$, but closer to the center of the shadow, the flux plunges steeply and smoothly to a value essentially indistinguishable from zero. As discussed by Elliot *et al.* (1989), the behavior near the center of the occultation shadow can be attributed to effects of extinction by a haze layer near the planetary surface. However, the haze layer model also implies that the true surface of Pluto lies substantially below the surface of the haze layer, with the consequence that the radius of Pluto's solid surface is no larger than 1143 km and might be as small as 1000 km. Our purpose here is to show that the general properties of the Elliot *et al.* (1989) lightcurve can be reproduced by a model atmosphere with a variable temperature profile and *no* extinction and that the corresponding temperature profile is not arbitrary, but has a physical basis in the calculations presented in Section II.

Using Eqs. (10–12), we inverted the model flux profile shown in Fig. 1 subject to the boundary condition that the atmosphere be isothermal at 106°K above r_I. The validity of the inversion was then tested by retrieving the input lightcurve using the direct theory. The inferred $T(r)$ relation from the lightcurve is shown as a solid curve in Fig. 3. This relation does not depend on the assumed gas composition. Note that the inversion only gives the profile down to $r =$

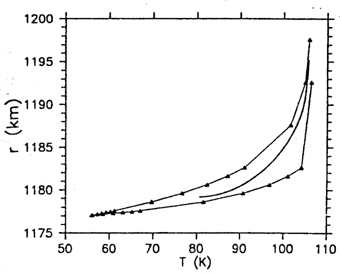

FIG. 3. Solid curve shows the $T(r)$ relation for a purely refractive model atmosphere (no haze layer) which reproduces the lightcurve shown in Fig. 1. Triangles show physical models discussed in text.

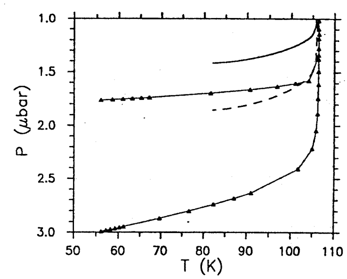

FIG. 4. Solid and dashed curves show $P(T)$ relations for the lightcurve shown in Fig. 1, for CH_4 and CO, respectively. Triangles show physical models.

1179 km ($T = 80$°K), and thus does not appear to reach the surface. Also plotted in Fig. 3 are two atmospheric temperature profiles computed using the physics discussed in Section II. The model with the closed triangles has a surface pressure of 1.8 μbar, and the model with the open triangles has a surface pressure of 3.0 μbar. Both models have a surface temperature of 55°K and $T_I = 106$°K. The radial zero-point of these two models is arbitrary.

Refraction models and physical models of Pluto's atmosphere are compared in a different way in Fig. 4. The curves with the triangles (closed, open) again represent the two physical models. The solid curve corresponds to the model shown with the solid curve in Fig. 3, assuming the refractivity of pure methane, while the dashed curve shows the same model offset in pressure by assuming the refractivity of pure carbon monoxide. The correct pressure scale must remain uncertain until the composition of Pluto's atmosphere can be independently determined, but it appears that the occultation data are consistent with a mixed CH_4–CO or CH_4–CO atmosphere.

V. SURFACE STATE OF ATMOSPHERIC GASES

The vapor pressures of CH_4 and CO over their pure ices are shown in Fig. 5. Also drawn are the dissociation pressures for CH_4 and CO contained in water-ice clathrate hydrate, based on Lunine and Stevenson (1985a) and more recent calculations (Lunine 1989a). The clathrate curves for N_2 and Ar are very similar to those for CO. For a surface temperature of 49°K at the poles,

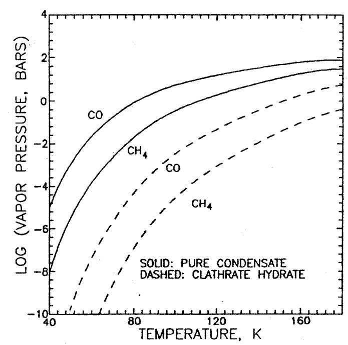

FIG. 5. Vapor pressures of carbon monoxide and methane over their pure frosts, using the polynomial fits of Brown and Ziegler (1979). Also shown as dashed curves are the equilibrium vapor pressures of these two species over clathrate hydrate, described in the text.

and the number density $n(r)$ can be found from the ideal gas equation of state $P = nk_BT$.

The refractivity $N(r)$ is proportional to $n(r)$. Following Hubbard *et al.* (1988), the total phase shift produced by the atmospheric for a ray with impact parameter r is

$$\Phi = \Phi_0(r) \quad (r > r_1),$$

$$\Phi = \Phi_0(r) + \Delta\Phi(r) \quad (r < r_1), \tag{8}$$

where $\Phi_0(r)$ is the phase shift for an isothermal atmosphere at temperature T_1, given by Eq. (3) of Hubbard *et al.* (1988), and $\Delta\Phi(r)$ is a correction to the phase due to temperature variations, given by

$$\Delta\Phi(r) = 2kN_1 \int_r^{r_1} \frac{ydy}{\sqrt{y^2 - r^2}} \left[\frac{e^{-\lambda_1 \eta}}{f} - e^{-\lambda_1(1 - r_1/y)}\right], \tag{9}$$

where $N_1 = N(r = r_1)$ and k is the wavenumber of the light. The calculation of the bending angle α and the normalized flux $\phi(r')$ (where r' is the observer's distance from the center of the shadow) then proceeds as discussed by Hubbard *et al.* (1988).

B. *The Inverse Problem*

It is also possible to derive the atmospheric structure from a lightcurve. If only the total normalized stellar flux $\phi(r')$ is available, we assume that this flux is strongly dominated by the near-limb image and neglect the contribution from the far-limb image. As we have verified by inverting calculated lightcurves, this approximation appears to be adequate for Pluto occultations because the far-limb image is potentially important only well within the half-flux locus in the shadow, where the total flux is strongly suppressed (see Fig. 1). Accordingly, the bending angle α of a ray with impact parameter r is given by

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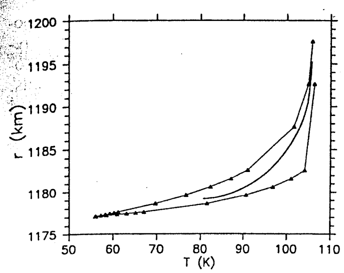

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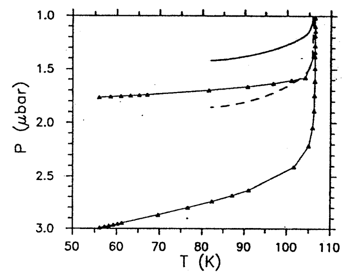

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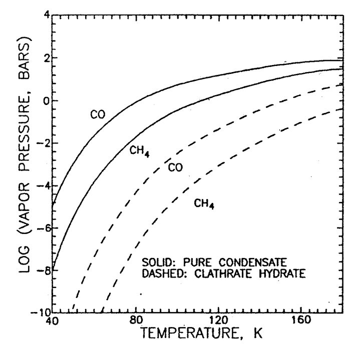

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the methane vapor pressure is 1 μbar, yielding the 50% gaseous mixing ratio of methane inferred above. (The value 49°K is somewhat lower than the IRAS-derived value of ~52 to 55°K based on results of Sykes *et al.* (1987), but we do not regard the difference as significant.)

Each of the candidate heavy gases (CO, N_2, and Ar) is much more volatile than CH_4; the vapor pressures at 49°K range from of order 100 μbars for argon to of order 10 mbars for N_2 and CO. In order for the heavier species to be equal in atmospheric abundance to CH_4 (i.e., to have a surface pressure of roughly a microbar) and be in some kind of vapor equilibrium with surface deposits, it would have to be in extremely dilute (roughly 1% for argon, and 0.01% for N_2 and CH_4) solid solution with CH_4. Another way of stating this is that CH_4 is the major ice at the surface; the heavier gas may be present in the methane gas in trace amounts.

The heavier gas could be locked in water ice as clathrate hydrate, based on Fig. 5, and perhaps slowly outgassed in response to atmospheric escape over time. Whether outgassing from clathrate would have been kinetically inhibited long ago by formation of a lag deposit is a difficult issue, since regolith formation and gardening processes could have aided continued outgassing (Lunine and Stevenson 1985b). Alternatively, the heavier gas may be periodically outgassed from deeper interior sources within Pluto; the processes by which volatile gases are released from the ice to enable outgassing deserve further study. The outgassing hypothesis can explain the present situation; the outgassing rate is sufficient, on a time-averaged basis, to oversaturate the atmosphere with respect to CH_4 (and hence form CH_4-ice) but not with respect to CO, N_2, or Ar because of their much higher vapor pressure. Loss is via atmospheric escape over geologic time.

An alternative heavy gas is CO_2. This candidate is highly unlikely, for two reasons: (1) The vapor pressure of CO_2 is ~10^{-15} μbar at 49°K; to have it in the atmosphere at a mixing ratio of 30% would require a surface temperature of 140°K, violating the IRAS temperature constraints. (2) Cosmochemical arguments presented below suggest that CO_2 is a minor component of Pluto's volatile budget. (Note that atmospheric thermal structure calculations presented here are not valid for an atmosphere containing significant amounts of CO_2.)

A strong dawn-to-noon temperature gradient could set up winds and consequent redistribution of heat across the surface. Whether this effect is important requires more detailed calculations than those presented here. The atmosphere picture presented above is consistent with CH_4 in vapor equilibrium with surface frosts, and CO, N_2, or Ar present as a background gas whose source is stochastic outgassing. As a final note, an equatorial surface temperature of 55°K based on IRAS data could be an overestimate because the Elliot *et al.* occultation data pertain to Pluto's dawn terminator. For a dawn occultation T could well be <50°K which would yield a steeper near-surface gradient as suggested by fitting occultation data. Pluto surface thermal models are more complex than those of asteroids because of long radiative times and deserve examination to better constrain the predawn temperature, which is highly sensitive to the thermal inertia. In fact, Hunten (1990) has investigated the effect of a diurnal boundary layer and finds that it acts to further quench the occultation lightcurve close to the surface, enhancing the effect discussed in this paper.

VI. COSMOCHEMICAL MODEL

While the identity of the heavier species is unconstrained from the above considerations, cosmochemical models coupled with Pluto's density provide some clues. Outer solar system bodies probably reflect a complex mix of matter having various origins. Chemically processed material from the inner solar nebula may have been mixed

with gas and grains falling from the surrounding giant molecular cloud, with some alteration of the CO-rich nature of the gas. This may have been further mixed with gases from the highly reducing subnebulas of the giant planets (Lunine 1989b, Prinn and Fegley 1989). The net mixture has a CO/CH_4 ratio in excess of 10–100, and *perhaps* orders of magnitude larger. The comet Halley CO/CH_4 value is ~1–10, but this reflects chemical fractionation processes which occurred as gases were incorporated, or trapped, in water ice (Lunine 1989a). The corresponding nebular CO/CH_4 ratio would have been >10–100.

Given a ratio of this order, the rock-to-ice ratio of a solid body such as Pluto formed in the outer solar nebula can be calculated; the high CO abundance implies that $<\frac{1}{3}$ of the oxygen is available to form water (Prinn and Fegley 1989). This leads to a rock-to-ice ratio of roughly 70% (by mass); the corresponding bulk density is 2.0 g/cm³ (Simonelli *et al.* 1989). This is fully consistent with the bulk density of the Pluto-Charon system. Hence, the bulk density plus cosmochemical arguments suggest that the heavy gas in Pluto's atmosphere is CO. The model predicts incorporation of gases into Pluto with ratios $CH_4:CO:N_2:Ar:CO_2$ corresponding (very roughly) to 1 : 1 : 0.1 : 0.01 : 0.001. Since CH_4 and CO_2 condense out under Pluto conditions their atmospheric abundances could not be reflective of this bulk mix; however CO, N_2, and Ar are so similar from a volatility standpoint that they may well be present in this bulk ratio. Testing this assertion would require a close flyby mission.

The alternative choice of atmosphere, a CH_4–N_2 mix, could be argued by analogy with Titan, but we reject it because of special circumstances associated with the origin of Titan. Titan's overall composition and orbital position at Saturn imply that Titan's bulk density reflects loss of water during accretion, plausible since for Titan $GM/r > L_S$ (the specific gravitational potential energy is greater than the latent heat of sublimation of water (Stevenson 1985)). The smaller satellites of Saturn have densities of 1.2–1.4 g/cm³, consistent with a Saturn nebula rich in CH_4, with most of the oxygen bound up in water ice. (In this model, Titan's N_2 is formed early on from NH_3; a recent discussion of this is in Lunine 1989a).

Pluto has $GM/r < L_S$, admittedly not by an order of magnitude, but still water loss during accretion is not likely. Whether water loss occurred during Charon formation is an open issue. Barring this last possibility, the Pluto/Charon system density is incompatible with a Titan-type chemistry, namely CH_4-rich, and hence a CH_4–N_2 atmosphere *without* CO is unlikely.

In summary, CO is the most plausible heavy gas in Pluto's atmosphere, on the basis of the system density and current understanding of outer solar nebula chemistry. Lesser amounts of N_2, Ar, and perhaps CO_2 are also predicted.

VII. ATMOSPHERIC ESCAPE

The temperature profiles derived in the previous section imply that the Pluto atmosphere will be escaping rapidly and that the escape mode is hydrodynamic rather than kinetic. This phenomenon has been discussed previously by Hunten and Watson (1982) and Trafton *et al.* (1988). Hunten and Watson pointed out that the escape rate is energy limited and employed formulae developed by Watson *et al.* (1981) to estimate an upper limit to the escape rate. The Watson *et al.* formulation has also been used by Trafton *et al.* (1988) in models for the atmospheric evolution of Pluto and Charon. In our opinion the Watson *et al.* formulation, while useful for estimating an upper limit to the escape rate, neglects some essential physics and is not particularly applicable to a planet with a tenuous atmosphere, such as Pluto. The basic problem is that Watson *et al.* (1981) treat the density at the lower boundary as a parameter to be determined by the estimated values for the escape rate and EUV heating level. While there may be some justification for this in a very deep atmosphere, the approach is questionable on Pluto where the atmospheric density is likely determined by surface properties (see also the discussion in Kasting and Pollack, 1986). Therefore, we reconsider the problem of estimating an upper limit to the CH_4 escape rate from Pluto.

The problem of escape is further complicated by the presence of two species with different atomic weights. We assume that diffusive equilibrium begins to dominate well below the level where the escape flux is determined and consequently the lighter constituent, CH_4, will be far more abundant in the upper atmosphere and escape far more rapidly. This allows us to neglect the heavier species in calculating the CH_4 escape rate. However, it is likely that the escape rate of the heavier constituent will be enhanced because of the drag forces exerted on the heavier constituent by the rapidly escaping CH_4 (Hunten 1984, Hunten *et al.* 1987). This problem deserves further study but is outside the scope of this work.

The hydrodynamic escape rate of an atmosphere is determined by the variation of atmospheric pressure and temperature with altitude. The atmospheric structure is governed by the energy and momentum equations. The energy and momentum balance equations in a spherically symmetric atmosphere may be written in terms of reduced variables as (cf. Watson *et al.* (1981), Eqs. (14), (4))

$$\frac{\tau^s}{\zeta}\frac{d\tau}{d\lambda} = \varepsilon + \lambda - \frac{7}{2}\tau - \frac{\psi}{2} \quad (15)$$

$$\frac{\partial P}{\partial \lambda} = \frac{P}{\tau}\left(1 - \frac{\partial \psi}{\partial \lambda}\right), \quad (16)$$

where the reduced variables τ, λ, and ψ represent the temperature T, radius r, and bulk velocity U normalized through

$$\tau = T/T_0$$

$$\lambda = GMm/k_BT_0r$$

$$\psi = mU^2/k_BT_0,$$

where m is now the mass of a methane molecule and T_0 the temperature at the lower boundary, at $r = r_0$. P is the atmospheric pressure as before; ζ is the molecular escape flux in normalized units and is defined by

$$\zeta = \frac{\phi_0 k_B r_0}{\kappa_0 \lambda_0}$$

where ϕ_0 is the molecular escape flux at r_0 (in cgs units for example) and κ_0 is the thermal conductivity at T_0. The thermal conductivity varies with temperature according to

$$\kappa(T) = \kappa_0 \tau^s;$$

Following Watson *et al.* (1981) we simplify the EUV heating calculation by assuming that all of the heat is deposited at a single level, λ_1. With this assumption the heating term, ε, becomes

$$\varepsilon = -\frac{\beta}{\zeta\lambda_1^2} \quad \lambda > \lambda_1$$

$$\varepsilon = 0 \quad \lambda < \lambda_1$$

with

$$\beta = \frac{S\lambda_0 r_0}{\kappa_0 T_0},$$

where S is the solar energy flux deposited in the atmosphere.

To accurately calculate the escape rate it would be necessary to find solutions to Eqs. (15) and (16) which pass through the critical point and match the boundary conditions near the surface of the planet and at infinity. However, an upper limit to the escape flux may be found with less difficulty. We note that above λ_1 the EUV heating term is absent and the problem is similar to the solar wind. If $\lambda_0 < 10$ the maximum escape flux may be written as (Parker 1964)

$$\zeta = \frac{2}{s+1}\frac{\tau_1^{s+1}}{\lambda_1^2}. \quad (17)$$

This equation relates the escape flux to the thermal structure in the lower atmosphere through the location (λ_1) and temperature (τ_1) of the EUV heating level; consequently, we may obtain ζ by solving Eqs. (15) and (16) in the region between λ_0 and λ_1. Because the EUV heating level occurs well below the critical point, ψ and $\partial\psi/\partial\lambda$ may be neglected in this region, greatly simplifying the problem. In actual practice it is necessary to first assume a value for the escape flux; Eqs. (15) and (16) are then solved simultaneously for the thermal structure, with λ_1 determined by the requirement that the overhead column abundance of CH_4 provides one optical depth in the EUV or 1×10^{17} cm^{-2}. The new values of λ_1 and τ_1 are used to calculate a new estimate for the escape flux and the process is repeated until a self-consistent solution is found. Results for Pluto (assuming a temperature of 106°K and base pressure of 1 μbar) are given in Table I. We note that the upper limit to the escape rate of 6×10^{10} cm^{-2} sec^{-1} is too small to cause significant adiabatic cooling near the 1 μbar level, justifying the neglect of this process in the models for the lower atmosphere presented earlier. An escape flux of 6×10^{10} cm^{-2} sec^{-1} implies a time constant for the depletion of the atmospheric methane inventory of $\sim 1 \times 10^9$ sec or about 30 Earth years.

It is instructive to compare the results calculated with this method to the Watson *et al.* (1981) approach. The upper limit derived here is slightly smaller but the limit occurs for a different reason. The Watson *et al.* formulation assumes that the escape flux is limited by the requirement that the temperature remain positive between the base of the atmosphere and the EUV heating level. In our formulation, the escape flux is limited by the requirement that the temperature remain positive at large distances from the planet. According to our calculations escape fluxes large enough to produce a deep temperature minimum between λ_0 and λ_1 would result in negative temperatures at large distances. This is basically a consequence of the weak EUV heating at Pluto's extreme distance from the sun.

TABLE I

CH_4 Escape Rates

	This paper	Watson *et al.* formula
$\lambda_0(CH_4)$	13.2	13.2
β	13.6	13.6
λ_1	5.3	3.8
ζ	0.07	0.09
ϕ_0	6.1×10^{10} cm^{-2} sec^{-1}	8.5×10^{10} cm^{-2} sec^{-1}

VIII. SUMMARY

We have shown from a study of occultation optics that a Pluto occultation lightcurve can exhibit a sharp break if a strong temperature gradient exists near the surface. We have also shown that a physical model of the atmosphere exhibits just such a temperature distribution and that the size of the gradient is comparable to that required to explain the lightcurves. We have not attempted a quantitative comparison with the data, and important questions still remain as to whether a purely refractive model can explain the very low flux value in the middle of the Elliot lightcurve. If the flux were to fall discontinuously from a value near 0.01 or 0.02 to precisely zero, due to the intersection of the ray and a solid surface, such a small drop might not be noticeable above the noise level in the data. There could also still be a very small haze layer near the surface, or perhaps further diurnal temperature excursions may play a role, as discussed by Hunten (1990).

It has been well known for some time that the stellar occultation flux is extremely sensitive to local temperature gradients in the occulting atmosphere. That is, large excursions in the stellar flux can be produced by small fluctuations of the atmospheric temperature about its mean value. In this paper we see that a decline of only about 20% in the atmospheric temperature could produce a major feature in the lightcurve. The stellar flux is so strongly quenched by this temperature gradient that Pluto stellar occultation observations may not be able to penetrate Pluto's atmosphere all the way to the surface.

Our model has two important features which must be noted when reconciling Pluto occultation data with data from mutual eclipses and occultations of Pluto and Charon (Tholen and Buie 1988).

First, the absence of a haze layer means that the atmosphere does not reduce the contrast of surface features seen from Earth, and thus the inferred surface albedo variations with rotational phase are the true ones (Marcialis 1988). This would not be the case if the atmospheric haze proposed by Elliot *et al.* exists, for their haze model has a lower limit of 0.19 for the vertical optical depth, such that the true surface albedo variations would have to be at least 20% larger than the inferred ones.

Second, the surface of Pluto must be at a radius just below the onset of the large temperature gradient, i.e., at about $r = 1180$ km (see Fig. 3). This value is 27 km larger than the Pluto radius of 1153 km derived by Beletic *et al.* (1989), or about 1.3 σ in Tholen and Buie's estimated error bar for Pluto's radius, and lowers the density of Pluto from 2.1 to about 1.9 g/cm^3.

After this paper was written, we found that Eshleman (1989) had independently reached similar conclusions about the effect of a near-surface temperature gradient on a Pluto occultation lightcurve and had likewise concluded that a purely refractive model was not ruled out by the data.

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