the cause of the time delay. The observed time-delay/period relation would then be explained if the drift time increases with the size of the clump.

Another possibility is that the time lag corresponds to the propagation time of a perturbing wave travelling from a low-energy- to a high-energy-X-ray-emitting region in the accretion disk with a group velocity $d\omega/dk$. Then the time delay corresponds to the wave travel-time. In this case it follows from the results in Fig. 1 that $d\omega/dk = a\omega^{\gamma}$, where ω is the angular frequency, k is the wave number, a is a constant and the value of γ is estimated at $\sim$0.5–0.9.

The soft-X-ray lag could occur by cooling of the X-ray-emitting plasma, or it could arise from some reverse perturbing wave travelling from the inner part of the disk to the outer part. The fact that the soft lag occurs in particular frequency regions would them imply that the reverse wave occurs in those regions.

Van der Klis *et al.*[11] observed soft-X-ray lags in Cyg X-2 and GX 5-1 at frequencies of less than $\sim$7 Hz, in addition to a hard-X-ray lag at QPO frequencies. Although the absolute values of these time lags are of the same order of magnitude as the hard X-ray time lags of Cyg X-1 at the corresponding frequencies, they have opposite signs. Those authors proposed a model in which the hard-X-ray lag at QPO frequencies is due to Compton scattering by a hot electron cloud and the soft lag at low frequencies is due to the spectral softening of X-ray shots; the softening exceeds the Compton-induced hardening at these low frequencies[11]. Stella *et al.*[12] observed soft lags of $\sim$8 ms in the $\sim$4-Hz QPO during persistent emission intervals in the Rapid Burster, which may be caused by Compton scattering by a cold electron cloud. Mitsuda *et al.*[18] observed a 70-ms hard lag in the 5-6-Hz QPO of Cyg X-2, but this phenomenon may not be due to Compton scattering, because of the large lag time.

Thus some of these phenomena suggest the existence of low-energy-gain (or loss) Compton scattering in these X-ray sources. None of them, however, suggests the existence of the high-energy-gain Compton scattering predicted in low-mass X-ray binaries by the model of White *et al.*[19], which is similar to the inverse Compton scattering model of Cyg X-1 (refs. 3, 4).

It is important to search for these phenomena in other X-ray sources, so as to elucidate the cause of the time-lag behaviour and to investigate whether or not the kind of time delay shown in Fig. 1 is related to the presence of a black hole. For the same reason it would be interesting to search for these phenomena in active galactic nuclei and to compare them with those of Cyg X-1.

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Occultation evidence for an atmosphere on Pluto

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On 9 June 1988, Pluto occulted a 12th-magnitude star[1]. Several observations of the occultation were obtained from Australia, New Zealand, and the south Pacific[2] and indicated that the initial decline in stellar flux was gradual, as would be expected if the starlight was defocused by an extended atmosphere around the planet. Here we interpret data obtained from the 1-m telescope at the University of Tasmania, Hobart, in terms of a theory for occultation by an atmosphere whose thickness is comparable to the planetary radius. The data can be satisfactorily fitted with a methane atmosphere at plausible pressures and temperatures. The surface pressures inferred from this single chord are uncertain by an order of magnitude, but are consistent with spectroscopic constraints.

To maximize the signal, observations were made in unfiltered light through a 30-arcsec aperture, including both Pluto and the occulted star. The detector was an EMI 9858A-S20 photomultiplier, and data were recorded at 1 kHz. At a later time, on 3 July 1988, it was possible to observe Pluto and the star separately with the same system at the same airmass, and the 9 June data were then corrected for the background from Pluto and sky, assuming that the regular variation of Pluto in the standard visual (V) filter (R. Marcialis, private communication) had the same relative amplitude in the unfiltered light. The data are shown in Fig. 1, in which ϕ represents the resulting normalized stellar signal, in units of the unocculted value, averaged to a time resolution of 1 s. The stellar signal displays a gradual variation characteristic of the presence of an atmosphere, rather than the abrupt change that would be expected from occultation of the star by an airless body.

At the time of the occultation at Hobart, one second of time corresponded to a projected sky-plane displacement of the star equal to 18.26 km with respect to Pluto's disk. Thus the total duration of the occultation, $\sim$115 s, corresponds to a chord length at Hobart of $\sim$2,100 km. This is comparable to the radius

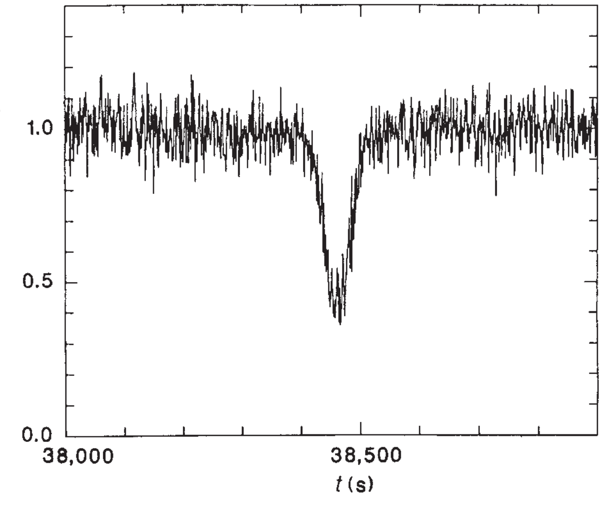

Fig. 1 Light curve observed at Hobart (t is seconds after 0:00:00 UT on 9 June 1988).

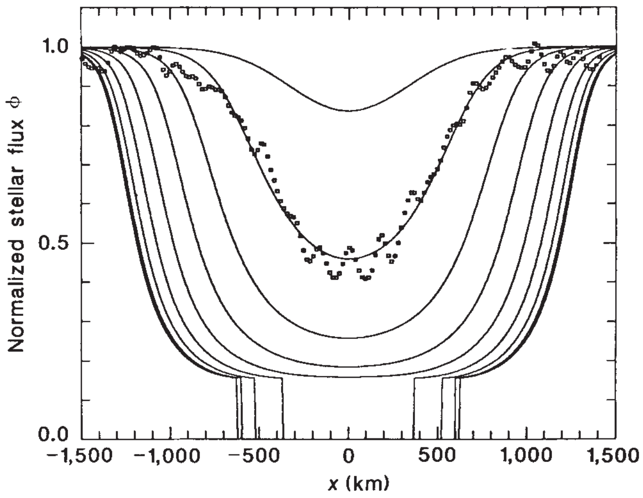

Fig. 2 Stellar flux plotted against position along chord, for nine chords in the warm atmosphere model. The chords shown range from $y_0 = 0$–1,335 km, in steps of 167 km, with the Hobart chord at $y_0 = 1{,}168$ km (26 km outside the limb) being fitted by least squares. Squares show Hobart data, smoothed by a gaussian window with a 2-s characteristic width.

of the solid planet (D. J. Tholen, private communication), $a_0 = 1{,}142 \pm 21$ km. These numbers are more remarkable than they appear, because we find that Hobart was actually slightly outside the geometrical shadow of the solid planet. Evidently the Pluto atmosphere revealed by the occultation at Hobart is comparable in thickness to the radius of the planet itself, as has been suggested for some time[3,4]. For this reason, the standard stellar occultation theory used for thin atmospheres[5,6] requires modification.

For the initial analysis, we derive a theory for an isothermal atmosphere at temperature T, which is taken to be the skin temperature of Pluto's atmosphere, or ~84% of the surface temperature. Temperatures that fit the data are, as discussed below, comparable to the surface temperatures expected for Pluto. With a surface pressure of only a few microbars, comparable to that of the Earth's atmosphere at 80 km, standard ideas on thermal structure may not apply; the isothermal assumption is the simplest and should be adequate over the small height range that controls the light curve.

We assume that the Pluto atmosphere is composed of a single molecular species with molecular mass m, and define the parameter

$$\lambda = GMm/rk_BT \qquad (1)$$

where G is the gravitational constant, M is Pluto's mass (which we take to be 1.29×10^{25} g), r is the distance from the centre of Pluto and k_B is Boltzmann's constant. Then the number density of molecules in Pluto's atmosphere in the region probed by the occultation is given by

$$n(r) = n_0 \exp(\lambda - \lambda_0) \qquad (2)$$

where n_0 is the surface density and $\lambda_0 = \lambda(r = a_0)$. Equation (2) is valid in hydrostatic equilibrium, which is well satisfied in this problem, and $\lambda \gg 1$, which is also well satisfied for plausible molecules and values of T in the region probed by the occultation. Because both the star and observer are at large distances from Pluto compared with r, one may replace Pluto's spherical atmosphere with an equivalent two-dimensional phase-changing screen[7] which changes the phase of an incoming plane wave from the star by an amount $\Phi(r)$, where r is now the distance from the centre of mass projected in the plane of the sky. Φ is calculated by integrating the refractivity of the gas, N, along a straight path through the atmosphere with impact parameter equal to the distance r, and multiplying by the wavenumber of the starlight, k. Because N is proportional to n, the integrated phase shift produced by the atmosphere on a wavefront of starlight is[8]

$$\Phi = kN\left(1 + \frac{9}{8\lambda}\right)\sqrt{2\pi r^2/\lambda} \qquad (3)$$

Equation (3) includes a first-order correction term in $1/\lambda$, which ultimately contributes a correction of about 1% to the occultation light-curve. All quantities are calculated at the radius of closest approach, that is, the projected distance from the centre of mass in the plane of the sky.

The total bending angle, α, of a ray after refraction by Pluto's atmosphere, with respect to its initial propagation direction, is

$$\alpha = -k^{-1}\frac{\partial\Phi}{\partial r}$$

We define r' as the observer's distance from the optical axis (defined by the line connecting the star and Pluto's centre), and D as the observer's distance from Pluto's centre (4.32×10^{14} cm). In general, for a spherical planet there will be two points where the total phase for a wavefront received by the observer is stationary: the near-limb point (−) and the far-limb point (+). We denote the values of r at these points as r_- and r_+ respectively. We have

$$D\alpha_- = r_- - r'$$

$$D\alpha_+ = r_+ + r'$$

respectively. For a given value of r', these equations can be solved numerically for r_- and r_+. The stellar flux is then calculated by obtaining the factors for one-dimensional defocusing in the radial direction:

$$\phi_\pm = \frac{1}{1 - D\dfrac{\partial\alpha_\pm}{\partial r_\pm}}$$

and then multiplying each by a factor that accounts for focusing in the orthogonal coordinate (which results from limb curvature). The total stellar flux, in units of the unocculted flux, is then given by[9–11]

$$\phi = \frac{r_-}{r'}\phi_- + \frac{r_+}{r'}\phi_+$$

We neglect Fresnel diffraction by the planet's surface, and instead set $\phi_\pm = 0$ whenever $r_\pm < a_0$.

A likely candidate for the major atmospheric molecule of Pluto is methane, whose ice absorption features appear in the planet's spectrum[12,13]. The maximum surface pressure of a methane atmosphere consistent with the spectroscopic evidence is 25 μbar (refs 13, 14). The surface temperature of Pluto could plausibly vary between 46–64 K, depending on the rate of heating by sunlight and on thermal properties[3]. The corresponding vapour pressure of methane varies between much less than a microbar to ~1 millibar, which suggests that a tenuous methane atmosphere could be produced by sublimation of surface ice. No other plausible molecule has an appropriate vapour pressure in the expected temperature range. Sykes *et al.*[14] find a sub-solar (presently equatorial) surface temperature of 58 ± 1 K, which corresponds to a methane vapour pressure of ~80 μbar. The geometry of the occultation was such that the Hobart data pertain to an atmospheric region nearly above Pluto's equator.

We consider two models (cold and warm) which roughly bracket the expected temperature range for a Pluto methane atmosphere in the occultation region. The cold model assumes an atmosphere of pure methane at $T = 50$ K ($\lambda_0 = 28$), and the warm model assumes pure methane at $T = 61$ K ($\lambda_0 = 23$), close to the maximum surface temperature. The other parameter that

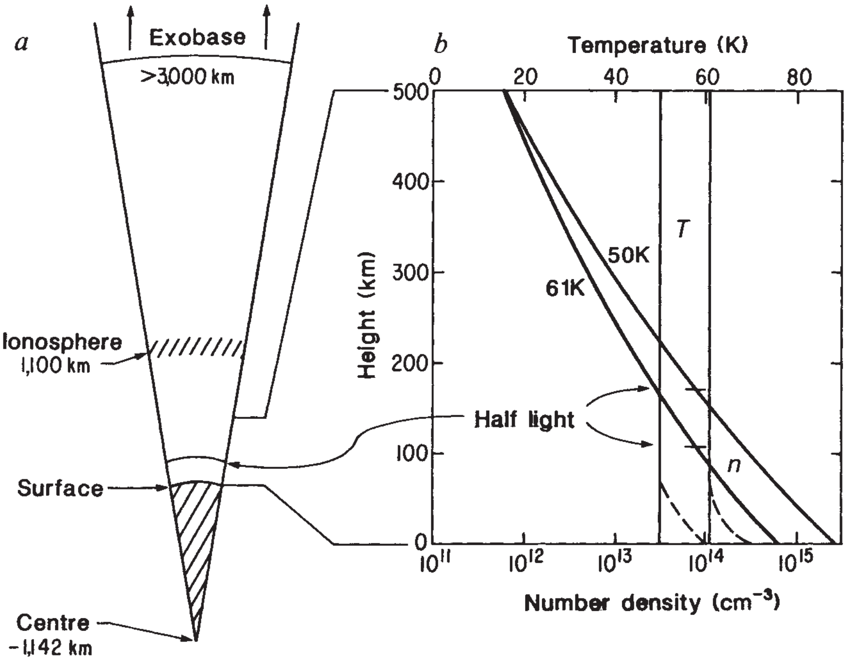

Fig. 3 A diagram of Pluto's atmosphere (*a*) and the warm (61 K) and cold (50 K) models (*b*). *a* Shows the main ray impact parameter at the level of half-light ($\phi=\frac{1}{2}$), the ionosphere and the exobase, above which molecules are essentially free of collisions and move on ballistic orbits. *b* Shows the temperature (T) and density (n) assumed for the bottom 500 km; the curvature of the density profile is due to variation of gravity with height. Dashed lines represent a possible modification of the isothermal profiles.

enters into the theory is the product $DN_0 = DN(r = a_0)$. Taking the refractivity of methane to be $N = N_{STP} = 4.41 \times 10^{-4}$ at STP[15], we then have

$$DN_0 = 5.1 \times 10^7 \frac{P_0}{T}$$

where P_0 is the surface pressure in μbar, T is in K, and D is in cm. For convenience we write $DN = K_0 \exp(\lambda)$, where $K_0 \equiv DN_0$. Thus the parameters that are adjusted to fit the Hobart data are λ_0, K_0, y_0 (the minimum value of r') and t_0 (the time of closest approach at Hobart).

Figure 2 shows results of a fit of the warm model to the Hobart data. The parameter λ_0 was held fixed and K_0, y_0 and t_0 were adjusted for best fit. In Fig. 2 we plot normalized flux ϕ as a function of position x along the chord (with $x = 0$ corresponding to closest approach). This model has $P_0 = 5$ μbar. As our data do not penetrate below the level $\phi \approx 0.46$, we do not observe the predicted rapid drop to $\phi = 0$ (total occultation) shown for more central chords (and which was observed from a station closer to the shadow's centre[16]), and we thus have no direct information about the location of a solid or opaque surface.

The cold model was fitted in a similar manner, yielding $y_0 = 1{,}234$ km and $P_0 = 18$ μbar. Although the grazing Hobart chord is fitted about as well by the cold model as by the warmer model, the central chords in the cold model exhibit a very different behaviour, because P_0 is sufficiently high that the star is never fully occulted by the surface. In contrast to the full stellar occultation for central chords predicted by the warm model, the cold model predicts that the stellar intensity should be enhanced by focusing near the centre of the shadow. The transition from a dark spot to a bright spot at the centre of Pluto's shadow occurs near $P_0 = 7$ μbar. The value of y_0 for the warm model is more consistent with a preliminary astrometric solution for the location of the Hobart chord with respect to the shadow's centre[16], indicating that this is the more satisfactory of the two models.

Figure 3*a* shows a sketch of the very extended atmosphere for heights up to 3,000 km, and Fig. 3*b* shows the density models for $T = 50$ and 61 K. For $T = 50$ K, the exobase is at 3,200 km, and the thermal escape flux, referred to the surface, is 4×10^9 cm^{-2} s^{-1}. Trafton[3] has suggested that the escape flux might be much greater, enough to exhaust any reasonable supply of methane. But Hunten and Watson[4] pointed out that such rapid escape would cool the upper atmosphere, so that the flux would in fact be limited to $\sim 5 \times 10^{10}$ cm^{-2} s^{-1}. The limiting factor is the available solar energy at high altitudes, deposited in the region of the ionosphere (shown hatched in Fig. 3*a*). At $T = 61$ K, the exobase is calculated to be well above 5,000 km, a sign that the atmosphere is on the verge of entering the state of energy-limited escape. Appreciable differences, as well as distortions from spherical symmetry, occur only at altitudes much higher than those probed by stellar occultation. Similarly, if there is a warmer region very near the surface, as indicated by the dashed lines in Fig. 3*b*, the effect should be small.

A combined analysis of all available data, together with coordinated observations of future Pluto occultations, should give substantial information about the atmosphere.

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