has been darkening[11] since 1954, and certain thermal models predict a large pressure increase at the present epoch[22]. Although these are plausible explanations, additional data and more modelling will be needed to fully explain our results. □

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Large changes in Pluto's atmosphere as revealed by recent stellar occultations

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Pluto's tenuous nitrogen atmosphere was first detected by the imprint left on the light curve of a star that was occulted by the planet in 1985 (ref. 1), and studied more extensively during a second occultation event in 1988 (refs 2–6). These events are, however, quite rare and Pluto's atmosphere remains poorly understood, as in particular the planet has not yet been visited by a spacecraft. Here we report data from the first occultations by Pluto since 1988. We find that, during the intervening 14 years, there seems to have been a doubling of the atmospheric pressure, a probable seasonal effect on Pluto.

The stars occulted by Pluto on 20 July 2002 and 21 August 2002 are referred to as P126 and P131.1; respectively, in the candidate list of refs 7 and 8. We organized a campaign for the P126 event, using fixed and portable telescopes in Argentina, Brazil, Chile, Ecuador, Peru and Venezuela, while the P131.1 occultation was observed at the Canada–France–Hawaii Telescope (CFHT) in Hawaii. Independent results obtained from sites in Chile, western continental USA and Hawaii are presented in a companion paper[9]. Owing to weather conditions and astrometric uncertainty before the event, we obtained only one positive detection of the P126 event in northern Chile near Arica, using a portable telescope and a broad-band CCD camera peaking in sensitivity near 0.6 μm (Fig. 1a). In contrast, the P131.1 event was observed with high signal-to-noise ratio in a narrow-band filter at 0.83 μm using the CFHT (Fig. 1b, c).

Our light curves are significantly different from those obtained in 1988. In particular, the Kuiper Airborne Observatory (KAO) data exhibited an abrupt change of slope in their lower part; this change of slope is absent in our data (Fig. 1a, b). This sudden drop was interpreted as being due to either absorbing hazes, or a sharp inversion layer in the lowest 20–50 km above Pluto's surface, connecting the isothermal upper atmosphere at temperature $T \approx 95$–110 K to the ground temperature at $T \approx 40$–60 K. Thus, our observations show that large changes in temperature or pressure, or both, occurred in Pluto's lower atmosphere between 1988 and 2002. However, no obvious differences in the shape of the upper part of the light curves are visible, suggesting that the thermal structure of Pluto's upper atmosphere has remained largely unchanged since 1988.

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Inversions of the light curves in terms of the atmospheric temperature T (Fig. 2a) and pressure p (Fig. 2c) as a function of the distance r to the planet's centre require, for each time step, the distance ρ of the observer to the centre of Pluto's shadow projected on Earth. This distance was retrieved with high accuracy (~15 km) for the 1988 event because several occultation chords were available. This, combined with KAO data error bars, provides the 1988 pressure profile shown in Fig. 2c (refs 4, 6). Conversely, with one chord at hand for the P126 and P131.1 events, the typical uncertainty on ρ is 250 km for both events, as derived from astrometric measurements available for each star and Pluto (see, for example, http://occult.mit.edu). From these measurements, the expected closest approaches ρ_{min} of the Arica and Hawaii stations to the shadow centre were $\rho_{min} = 975 \pm 250$ km and $\rho_{min} = 610 \pm 250$ km, respectively.

Only the higher-quality P131.1 light curve has been inverted, and to within the astrometric uncertainties described above, all our inversions show that the temperature or pressure profiles (or both) have drastically changed since 1988. In particular, taking the nominal astrometric solution corresponding to $\rho_{min} = 610$ km,

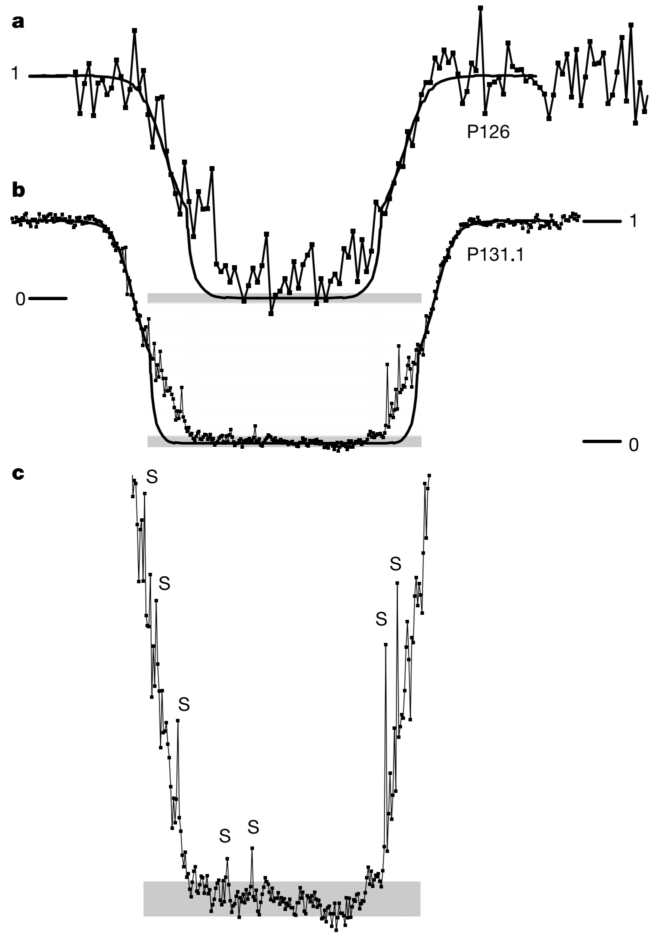

Figure 1 Dimming of the stars P126 (20 July 2002) and P131.1 (21 August 2002) during their occultations by Pluto's atmosphere. **a**, The P126 light curve, binned in 2-s time intervals, was obtained from northern Chile (longitude = 69° 45′ 51.5″ W, latitude = 18° 26′ 53.8″ S, altitude 2,500 m) with a 30-cm Schmidt–Cassegrain portable telescope and Kodak-401E CCD camera without filter, sensitive between 0.4 and 0.9 μm, with a peak near 0.6 μm. The horizontal length of the shaded rectangle represents a duration of 2 min centred at 01:44:03 UT. The total unocculted flux (P126 + Pluto + Charon) is normalized to unity (label "1"). The expected level corresponding to the complete extinction of the star (label "0") is indicated by the position of the shaded rectangle, whose vertical extension represents the uncertainty of photometric calibration. **b**, The P131.1 light curve, obtained at the Canada–France–Hawaii 3.55-m *f*/8 telescope (CFHT) equipped with a MIT/LL CCID20 in the I band (0.83 ± 0.1 μm) with a exposure time of 1 s and cycle time of 1.583 s. The length of the shaded rectangle now corresponds to a duration of 5 min, centred at 06:50:35 UT. Graphs **a** and **b** are plotted with the same vertical scale from "0" to "1". The two horizontal scales are such that equal horizontal lengths represent equal distances traveled by Pluto in the plane of the sky. Both light curves have absolute timing accuracy of ~0.3 s. The solid curve in **a** and **b** is a smoothed version of the data obtained from Kuiper Airborne Observatory (KAO) during the 9 June 1988 Pluto occultation[3–6]. **c**, A vertically stretched version of **b**, enhancing the spikes ("S") and the steady decrease of signal in the bottom part of the light curve.

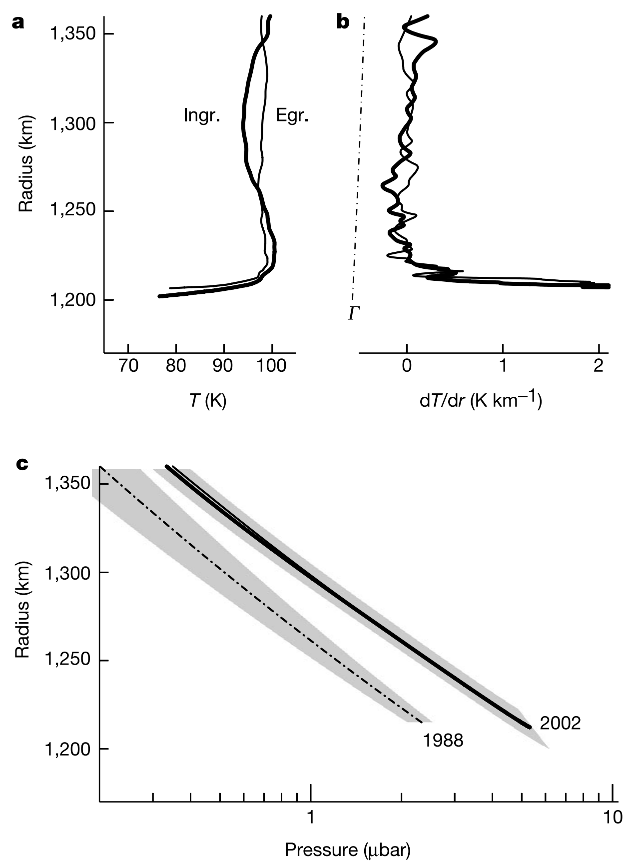

Figure 2 Temperature and pressure profiles of Pluto's atmosphere derived from the inversion of the P131.1 light curve. This inversion[17] assumes a spherically symmetric and transparent atmosphere. It first provides the atmospheric refractivity profile, then the density profile for a given gas composition, and finally the temperature profile, assuming an ideal gas in hydrostatic equilibrium. We assume for Pluto a pure molecular nitrogen[6] atmosphere, and we take into account the curvature of Pluto's limb as well as the variation of the acceleration of gravity g with radius, assuming a mass of 1.31×10^{22} kg for Pluto[18]. **a**, Pluto's atmospheric temperature profiles $T(r)$ at ingress (thick curve) and egress (thin curve). The radius is the distance to the planet centre, for the nominal astrometric solution discussed in the text. **b**, The corresponding temperature gradient profiles dT/dr. The dash-dotted line provides the adiabatic lapse rate profile $\Gamma = -g/c_p$, to the left of which the atmosphere would become convectively unstable, where $c_p = 1.04 \times 10^3$ J K^{-1} kg^{-3} is the specific heat at constant pressure for N_2. **c**, The corresponding pressure profiles. The dash-dotted line is the pressure profile derived from the KAO lightcurve of 9 June 1988 (ref. 6), with the associated error domain[6], shown as the shaded region. The ingress and egress profiles derived from the CFHT light curve of 2002 are the nearly coincident thick and thin solid lines, respectively. The error domain for the 2002 profiles only takes into account the photometric uncertainties in the levels "0" and "1" shown in Fig. 1b. The effects of the astrometric uncertainty are discussed in the text.

we obtain essentially the same temperature profile $T(r)$ as in 1988, including a strong inversion layer below $r = 1{,}215$ km, but with a systematic and significant increase of pressure at all radii (Fig. 2c). This pressure increase reaches a factor of 2.1 at $r = 1{,}215$ km, where $p = 5.0 \pm 0.6\,\mu$bar in 2002, while $p = 2.33 \pm 0.24\,\mu$bar in 1988 (ref. 6).

Figure 1c shows that the bottom of the P131.1 light curve is generally flat for about 200 s, with a small but significant decrease of signal over this time interval. Taking again $\rho_{\rm min} = 610$ km, we find that during this 200-s interval the image of P131.1 scanned Pluto's limb at a constant radius of 1,205 km, with latitudes ranging from 61° S (for the onset of occultation, or 'ingress', also known as 'immersion') to 8° S (for the termination of occultation, 'egress' or 'emersion'). This steady decrease of signal could conceivably be due to the presence of morning hazes above the egress point. Perhaps more probably, it indicates an egress temperature about 10 K smaller than the ingress temperature at $r = 1{,}205$ km. The P131.1 star ingress probed the south pole region now constantly in sunlight, while the egress probed the morning limb of the equatorial region, which emerged after 3.2 days in darkness. (Note that we adopt the International Astronomical Union convention, in which Pluto's south pole is currently tilted toward Earth). Taking a thermal inertia of $15\,{\rm J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, derived from Pluto's thermal light curve[10], and using a subsolar latitude of 29.7°S at Pluto in August 2002, we estimate that the dawn equatorial ground temperature is ~25% lower, that is, 12–15 K cooler, than the polar temperature for a uniform surface albedo. However, according to a recent surface model[11], Pluto's south pole is covered by methane-rich areas while the equator is predominantly covered by darker tholins. For this case, we estimate a ground polar temperature of ~53 K and a dawn equatorial temperature of 45 K. These numbers compare well with the difference between the ingress and egress temperatures near $r = 1{,}205$ km, suggesting that the lower 10–40 km (0.25–1 scale height) of the atmosphere are affected by surface boundary layer effects.

Conversely, our observations do not reveal a significant temperature difference between egress and ingress (and also with 1988) in the isothermal region above $r = 1{,}220$ km. This can be understood in the methane-thermostat model of ref. 12, which demonstrates that the upper-atmosphere temperature is robustly controlled at ~100 K by the radiative properties of atmospheric CH_4, almost independently of its abundance. Accounting for the diurnally averaged insolation at the south pole and the equator, we find that the upper-atmosphere temperatures at ingress and egress should only differ by 3 K at radiative equilibrium, well within the uncertainties of our measurements.

The P131.1 light curve exhibits spikes (Fig. 1c) which correspond to local temperature gradients of up to ${\rm d}T/{\rm d}r \approx \pm 0.05\,{\rm K\,km^{-1}}$ over vertical scales of 5–15 km in the retrieved temperature profiles (Fig. 2b), yielding temperature fluctuations of $\Delta T \approx \pm 0.5$–0.8 K over these scales. The spikes are more conspicuous than in 1988 (refs 4, 6), and reveal a dynamical activity in Pluto's atmosphere. Its origin could be gravity waves launched by convection in a putative lower troposphere, and/or turbulence triggered by shears driven by strong winds between Pluto's lit and dark hemispheres. The observed values of $|{\rm d}T/{\rm d}r|$ remain well below the adiabatic temperature lapse rate Γ (Fig. 2b), indicating that either convective instability is not reached, or that stronger local gradients exist but are smoothed out over the ~500 km that a stellar ray travels in the atmosphere before being significantly refracted towards Earth.

We have tested the robustness of our results to changes in the P131.1 astrometric solution. We find that varying $\rho_{\rm min}$, everything else been equal, mainly displaces vertically the temperature profile $T(r)$, while multiplying the pressure at all levels by a roughly constant factor with respect to the nominal solution with $\rho_{\rm min} = 610$ km. In particular, a solution that leaves the pressure unchanged at all levels (to within 10%) since 1988 can be found with $\rho_{\rm min} = 550$ km. However, the whole temperature profile $T(r)$, including the inversion layer, would then be shifted downward by about 30 km. Such a large variation of Pluto's thermal structure in the lower atmosphere since 1988 seems unlikely. The inversion layer is best physically explained through the absorption by atmospheric methane, and its existence does not depend sensitively on the CH_4 abundance (although the precise value of the temperature gradient does[13]). Moving the inversion layer downward by 30 km from its $r = 1{,}200$–$1{,}220$ km nominal level would imply a dramatic shrinking of the 40-km-deep troposphere advocated in ref. 14 on the basis of the 1988 occultation. Such a troposphere would presumably be maintained by convection, perhaps driven by the large temperature gradients across Pluto's surface[10]. It should be fairly stable over a 14-year timescale, and it is supported by the presence of spikes in the CFHT light curve, as discussed above.

In contrast, a twofold increase in pressure in the 14 years since 1988 is not at odds with expectations of nitrogen cycle models[15,16], despite Pluto's increasing heliocentric distance. The best-fitting models[15], in which N_2 frost distribution and associated atmospheric pressure are calculated as a function of season, do predict an increase of pressure by a factor of about 2 between 1990 and 2000; this increase follows equinox on Pluto in 1987, leading to the current sublimation of the south polar cap as it goes into sunlight. Thus, although the seasonal models are only partly successful in reproducing the observed albedo patterns-particularly the currently large north polar cap and the relative darkness of the south polar regions, they must adequately capture the physics of hemispheric volatile exchange. □

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