The recent expansion of Pluto's atmosphere

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Stellar occultations—the passing of a relatively nearby body in front of a background star—can be used to probe the atmosphere of the closer body with a spatial resolution of a few kilometres (ref. 1). Such observations can yield the scale height, temperature profile, and other information about the structure of the occulting atmosphere. Occultation data acquired for Pluto's atmosphere in 1988 revealed a nearly isothermal atmosphere[2] above a radius of ~1,215 km. Below this level, the data could be interpreted as indicating either an extinction layer or the onset of a large thermal gradient, calling into question the fundamental structure of this atmosphere. Another question is to what extent Pluto's atmosphere might be collapsing as it recedes from the Sun (passing perihelion in 1989 in its 248-year orbital period), owing to the extreme sensitivity of the equilibrium surface pressure to the surface temperature. Here we report observations at a variety of visible and infrared wavelengths of an occultation of a star by Pluto in August 2002. These data reveal evidence for extinction in Pluto's atmosphere and show that it has indeed changed, having expanded rather than collapsed, since 1988.

Pluto's predominantly nitrogen atmosphere is in vapour pressure equilibrium with the surface ice, and consequently can undergo large changes in pressure in response to small changes in surface-ice temperature[3]. In 1988, when this atmosphere was probed with a stellar occultation from a variety of sites[4–6], the light curve revealed a pronounced 'kink' (an abrupt change of slope, described below) that could be interpreted as the abrupt onset of either a thermal gradient[7,8] or an extinction layer[2,5]. The kink was observed during the onset of occultation ('immersion', also known as 'ingress') and at its termination ('emersion', also known as 'egress'). In order to resolve these issues, attempts have been made for over a decade to observe additional Pluto occultations[9,10]. None proved successful until our observations of the 20 July 2002 occultation of the star 'P126A'[10], from which we determined that Pluto's atmosphere had changed[11,12] since 1988, but the data set was not sufficient for further conclusions[11].

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The 21 August 2002 occultation of the star 'P131.1'[10] (R-band magnitude $R = 15.7$ mag, K-band magnitude $K = 13.3$ mag) was predicted (http://occult.mit.edu/research/occultations/Candidates/Predictions/P131.1.html), and subsequently observed from several telescopes in Arizona, California and Hawaii (see Fig. 1, Table 1, and Supplementary Table 1). Although most of these observations were at visible wavelengths with no filtering, we probed for possible extinction with additional wavelength coverage: an H-band infrared filter on the UK Infrared Telescope (UKIRT) and continuous coverage between 0.8 and 2.5 μm with the SpeX[13,14] spectrograph on the Infrared Telescope Facility (IRTF). This data set is unique, in that (1) it provides wide spatial coverage over Pluto's disk, which is essential for the accurate astrometric solution needed for derivation of the atmospheric information, and (2) it has the wavelength coverage needed to allow some distinction between extinction and differential refraction effects. The data from the University of Hawaii 2.2-m telescope (UH 2.2-m) had the best signal-to-noise ratio and the highest time resolution—0.5 s, during which Pluto's shadow moved only 3.3 km (the highest spatial resolution yet achieved within Pluto's atmosphere). These data are plotted as the solid line in Fig. 2, along with the 1988 data from the Kuiper

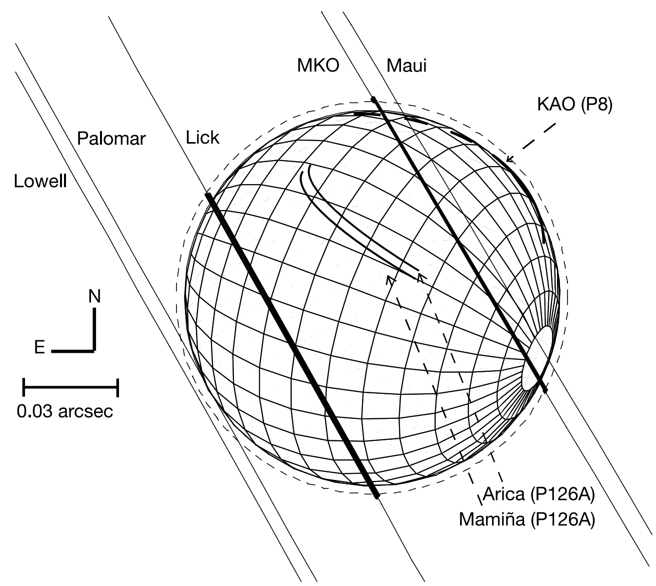

Figure 1 Occultation probes of Pluto's atmosphere. Occultation chords are overlaid on a schematic of Pluto, which is plotted as it appeared during the P131.1 occultation with the north rotational pole (IAU definition) behind the limb of the planet (sub-Earth latitude and east longitude of −28.1° and 38.1°, respectively). Straight lines indicate the occultation chord paths for all successful observing stations. The Lowell chord grazed the upper atmosphere with the stellar flux dropping only 6%. The two bold chords for Mauna Kea Observatory (MKO) and Lick represent the data used to calculate the astrometric solution upon which other analyses in this work was based. For this solution, the closest approach to the centre of Pluto's shadow was 597 ± 32 km for the MKO telescopes and 600 ± 32 km for Lick, and the velocities of Pluto's shadow were 6.8489 km s^{-1} and 6.7293 km s^{-1} for the two sites, respectively. The dotted circle indicates the solution's half-light radius (in the shadow) of 1,213 ± 16 km, which compares with 1,154 ± 20 km determined from the 1988 data. Assuming no extinction above the half-light levels, these correspond respectively to 1,283 ± 9 km and 1,214 ± 20 km in Pluto's atmosphere, after correcting for the smaller size of the shadow, due to refraction[5]. Over-plotted are the equivalent ground-paths of the P126A Mamiña chord obtained by our group[11] as well as the P126A Arica chord[12] and the P8 KAO chord[5]. These curves are the straight chord lines from the past events[5,11,12] projected onto P131.1 Pluto coordinates. The solid (right) portion of the KAO chord is in front of the planet, while the dashed (left) portion is behind the planet's limb. All chord directions (immersion to emersion) are from southwest to northeast, except the KAO chord which is reversed.

Table 1 **Observations from Mauna Kea and Lick observatories**

Site, telescope (aperture, in m)	East longitude (° ′ ″)	Latitude (° ′ ″)	Instrument	Wavelength	Recording interval (21 Aug. 2002 UT)	Cycle time (s)	Integration time (s)	SNR*	Observers
Lick									
Shane (3.0)	−121 38 14	37 20 34	PCCD[23]	Visible†	06:34:00–07:03:58	1.0	1.0	16	E.W.D., C.B.O.
Mauna Kea‡									
IRTF (3.0)	−155 28 19	19 49 34	SpeX[13,14]	0.8–2.5 μm	06:29:09–07:11:20	12.7–15.5§	10.0	57	J.L.E., K.B.C., J.T.R.
UH (0.6)	−155 28 16	19 49 18	PCCD[23,24]	Visible†	06:34:26–07:11:25	7.0–8.0§	5.0	24	M.J.P., S.Q.
UH (2.2)	−155 28 10	19 49 23	Williams CCD	Visible†	06:39:49–06:59:49	0.5	0.5	103	J.M.P., B.A.B., D.R.T.
UKIRT (3.8)	−155 28 13	19 49 21	IRCAM[25]	H	06:41:12–06:57:03	3.3–4.8§	1.5	39	D.J.T., D.J.O., S.K.L.

For a complete listing of all attempted observations, see Supplementary Table 1 and the independent results in the companion paper[12].
*'SNR' is the signal-to-noise ratio for the signal from the unocculted star integrated over a time interval corresponding to 60 km (about a scale height) of shadow motion[17]. The SNR for the Lick data was lower than expected from the size of the telescope aperture compared with other sites due to poor observing conditions (5-arcsec images at Lick compared with 0.5-arcsec images at Mauna Kea Observatory).
†'Visible' means that an unfiltered CCD was used.
‡For the Mauna Kea Observatory telescopes: IRTF is the Infrared Telescope Facility, UH is the University of Hawaii, and UKIRT is the United Kingdom Infrared Telescope.
§Variable cycle times occur for a variety of reasons that will be discussed elsewhere.

Airborne Observatory (KAO), which is plotted with triangles. The kink seen in the earlier occultation is not evident, indicating a significant change in Pluto's atmospheric structure between 1988 and 2002.

In order to establish exactly what regions of Pluto's atmosphere were probed by our light curves, we determined the UH 2.2-m and Lick half-light times (given in Supplementary Table 2) and then carried out a circular astrometric solution (Fig. 1).

We investigated the extinction properties of Pluto's atmosphere by comparing the minimum normalized stellar fluxes observed in several different spectral bands. Figure 3 shows that the minimum fluxes increase as a function of wavelength—a behaviour that would not be expected if the minimum flux were determined by refraction (as would be the case for the thermal-gradient model). This trend is just what we would expect, however, from extinction by submicrometre-sized particles[15]. In contrast with the 1988 data, the extinction exhibited in the present data does not have an abrupt upper boundary (to which the kink in the light curve has been attributed). One source of submicrometre particles could be photochemical production in Pluto's atmosphere[16]. An alternative explanation for the trend seen in Fig. 3 is that we are seeing a small amount of flux from an unresolved, redder star ($K \approx 16.0$ mag) that was

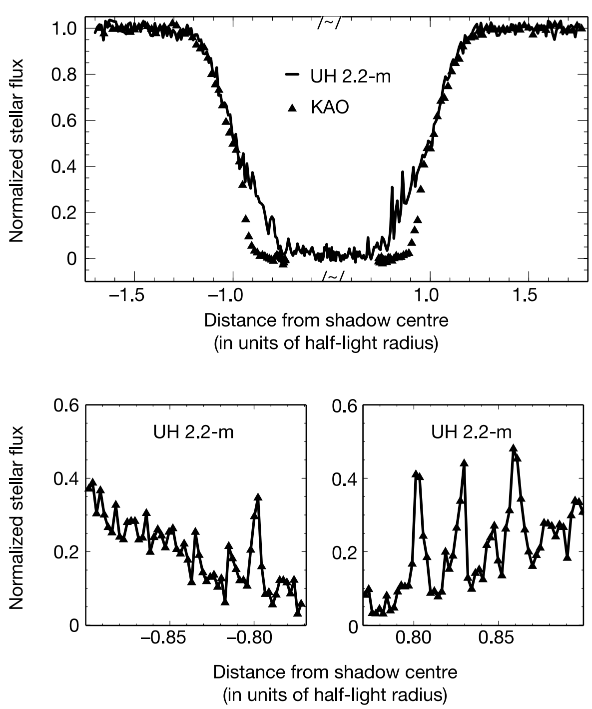

Figure 2 Pluto occultation light curves. Top panel, the UH 2.2-m data from the 21 August 2002 event (line) and the KAO data from the 9 June 1988 event (triangles) have been plotted versus distance from the centre of their occultation shadows. The distance scale has been normalized in units of half-light radius and broken at the centre, making the UH 2.2-m light curve appear as a continuous plot (corresponding to the physical observation of a continuous time series). The KAO data have been averaged over 1.6 s (8 points) and the UH 2.2-m data over 2.0 s (4 points). Since the data have been plotted versus distance from the centre of Pluto's shadow, the central part of the UH 2.2-m light curve exhibits higher frequency variations than would be apparent if the abscissa were time (see, for example, Fig. 1 of the companion paper[12]). The 1988 light curve from the KAO drops sharply to zero just below half light, whereas the 2002 light curve has no such 'kink'. Since the KAO light curve did not probe as deeply into the shadow as the UH 2.2-m light curve, there is a gap in its centre (although the entire light curve has been plotted). Bottom panels, portions of the UH 2.2-m light curve plotted at their full time resolution of 0.50 s. 'Spikes' (short flashes of starlight[1]) are visible on both the immersion (left) and emersion (right) plots. Such features are barely discernable in the highest time-resolution plots of the KAO data[5] (not presented here). The spikes are caused by small density variations in Pluto's atmosphere—due to atmospheric waves of some form and/or turbulence—that occur on short spatial scales[1]. Note that spikes of similar amplitude appear at 0.8 of a half-light radius from the centre on both the immersion and emersion light curves.

not occulted by Pluto. Such a star could be located as close as ~0.03 arcsec (Fig. 1) to P131.1—a possibility that could be checked with high-resolution imaging (a difficult task, even for the Hubble Space Telescope).

Considering the possible pervasive extinction in Pluto's atmosphere, standard techniques for determining the atmospheric structure from an occultation light curve must be used with caution, since these are based on a clear-atmosphere assumption[17] or postulate a specific extinction model[2]. Bearing this in mind, we used only those portions of the light curve corresponding to radii above 1,220 km (to remain above the extinction level in the model used for the 1988 data) to establish the equivalent isothermal temperatures for an N_2 atmosphere. These are 107 ± 4 K and 101 ± 3 K, respectively, for immersion and emersion, and their mean is 104 ± 2 K. This is virtually the same as that obtained in 1988: 104 ± 8 K (the smaller error bar than previously published[2] reflects a smaller error bar on Pluto's mass[18]). Hence the equivalent isothermal temperature of Pluto's atmosphere at the few microbar level has not changed by a detectable amount.

Finally, we inverted the UH 2.2-m light curve (Fig. 2), for which the pressure versus radius profiles are shown in Fig. 4. Here, for comparison, we have also plotted the pressure profiles for the KAO data from 1988, with the level of the kink indicated for reference. According to the haze model for the 1988 data, all extinction effects should occur below this level (although we cannot determine a maximum altitude for any extinction in the 2002 data). These pressure profiles apply for the clear-atmosphere assumption, but we note that on the scales used in Fig. 4, a break in the pressure profiles at this level (caused by the kink) is not perceptible (in contrast, the shapes of the temperature profiles are highly dependent on the presence of the kink[17]). Hence we conclude that the pressure in Pluto's atmosphere within the 1,200–1,280 km radius range has increased by about a factor of two between 1988 and 2002. This corresponds to an expansion of about 40 km for the isobars in the region probed by the occultation.

If the temperature structure between this region and the surface has remained the same, as it apparently has within the region probed by the stellar occultations, then the surface pressure has also increased by a factor of two. Neptune's satellite Triton—a body similar to Pluto in size, density, and atmospheric constituents—experienced a smaller pressure increase[19,20] during 1989–97. Surface-pressure increases on both of these bodies would be driven by regaining vapour-pressure equilibrium in response to small increases in the temperature (~1 K) of nitrogen surface ice. The fact that both have experienced increased pressure leads one to look for a common cause, such as increased solar output—but this has not occurred[21]. Possible reasons for surface-temperature increases include (1) a darkening of the surface ice, so that more sunlight is being absorbed and (2) the effects of thermal inertia and the large obliquity of these bodies. Photometric observations show that Pluto

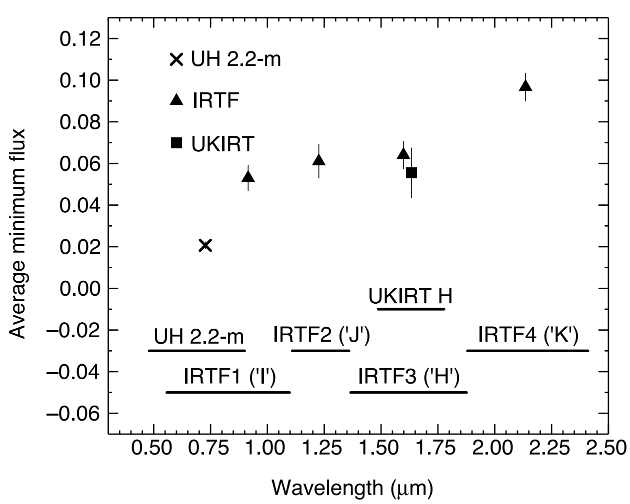

Figure 3 Minimum stellar fluxes versus wavelength. Horizontal lines indicate the pass bands for the UH 2.2-m observations, the H filter used on UKIRT, and the four SpeX 'bands' (crudely approximating the I, J, H and K bands); the points indicating the minimum fluxes are plotted at the effective wavelength for each pass band. Each minimum flux, expressed as a fraction of unocculted stellar flux, and its error bar was derived by averaging the central 216.5 s of the light curve for each data set. The full-scale and zero level of each light curve were calibrated with observations of Pluto-Charon and the star when they were well separated before and after the occultation. The wavelength dependence suggests that the minimum occultation flux is determined by extinction in Pluto's atmosphere. Note that the minimum flux level of the SpeX 'K' band is at about 0.08 of the unocculted stellar flux. By assuming that this flux at K applies to a clear atmosphere, we estimate lower limits on the slant-path optical depths ranging between 0.0 at 'K', through to 0.8 at 'J', and possibly larger than 2 in the visible. Mie[15] light-scattering calculations show that spherical particles with radii near 0.2 μm and refractive indices representative of tholins[26] have an appropriate wavelength dependence in extinction efficiencies to produce such a curve[27]. However, modelling of the growth and sedimentation of photochemically produced spherical aerosols[28] suggests that realistic haze production rates are not sufficient to produce such large opacities. Whereas single Mie spheres prove inadequate in these models, aggregate particles may provide a solution as they can have extinction efficiencies up to ten times larger than equivalent volume spheres of the same material[29]. The likelihood of aggregate haze particles in Pluto's atmosphere is strengthened by recent studies[27,30] showing it is likely that photochemical hazes on Titan are aggregate in nature.

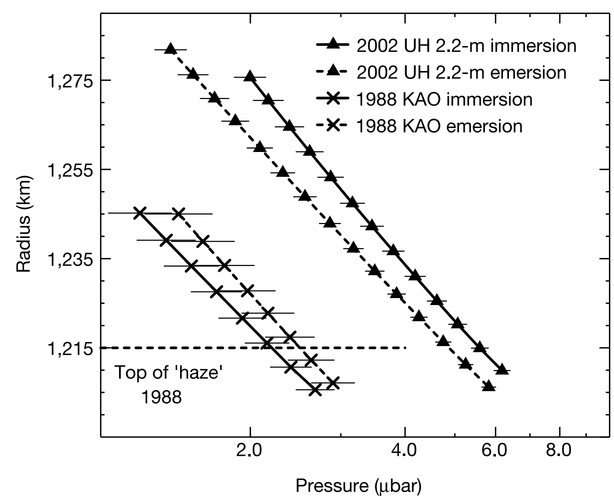

Figure 4 Pressure profiles for 21 August 2002 and 9 June 1988. Pressures obtained from inversions[17] of the two occultation light curves, for immersion and emersion, have been plotted on a log-linear scale versus distance (in km) from the centre of Pluto (the surface radius is poorly constrained[17], with $1,175 \pm 25$ km covering the likely range). The error bars indicate a one standard deviation error, and since these errors are highly correlated[17], the scatter between adjacent points is much less than the error bars. The non-overlapping error bars for the 2002 immersion and emersion pressure profiles may be due to noise or a small discrepancy between the radius scales for immersion and emersion. The large difference between the atmospheric pressures derived from the two occultations indicates that Pluto's atmospheric pressure has increased by a factor of two between 1988 and 2002. A surface-pressure increase by a factor of two on a body with its surface pressure in vapour-pressure equilibrium would imply a temperature increase of the N_2 frost of 1.3 K for the likely range of surface pressures applicable to Pluto[17]. If this temperature change in the frost were brought about by changes in the average albedo of Pluto, it would require a decrease in the red albedo, for example, from 0.64 to 0.59. Effects of thermal inertia[22] could be at work as well, which would lessen the contribution of additional heat needed from an albedo change.

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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