PLUTO’S ATMOSPHERE FROM THE 2015 JUNE 29 GROUND-BASED STELLAR OCCULTATION AT THE TIME OF THE NEW HORIZONS FLYBY*

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Received 2016 January 20; accepted 2016 February 25; published 2016 March 10

ABSTRACT

We present results from a multi-chord Pluto stellar occultation observed on 2015 June 29 from New Zealand and Australia. This occurred only two weeks before the NASA New Horizons flyby of the Pluto system and serves as a useful comparison between ground-based and space results. We find that Pluto’s atmosphere is still expanding, with a significant pressure increase of \(5 \pm 2\%\) since 2013 and a factor of almost three since 1988. This trend rules out, as of today, an atmospheric collapse associated with Pluto’s recession from the Sun. A central flash, a rare occurrence, was observed from several sites in New Zealand. The flash shape and amplitude are compatible with a spherical and transparent atmospheric layer of roughly 3 km in thickness whose base lies at about 4 km above Pluto’s surface, and where an average thermal gradient of about 5 K km\(^{-1}\) prevails. We discuss the possibility that small departures between the observed and modeled flash are caused by local topographic features (mountains) along Pluto’s limb that block the stellar light. Finally, using two possible temperature profiles, and extrapolating

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*Partly based on observations made with the ESO WFI camera at the 2.2 m Telescope (La Silla), under program ID 079.A-9202(A) within the agreement between the ON/MCTI and the Max Planck Society, with the ESO camera NACO at the Very Large Telescope (Paranal), under program ID 089.C-0314 (C), and at the Pico dos Dias Observatory/LNA, Brazil.
our pressure profile from our deepest accessible level down to the surface, we obtain a possible range of 11.9–13.7 μbar for the surface pressure.

Key words: Kuiper belt objects: individual (Pluto) – occultations – planets and satellites: atmospheres – techniques: photometric

1. INTRODUCTION

Ground-based stellar occultations probe Pluto’s atmosphere at radii ranging from $r \sim 1190$ km from the planet center (pressure $p \sim 10$ μbar) up to $r \sim 1450$ km ($p \sim 0.1$ μbar). In a previous work (Dias-Oliveira et al. 2015, DO15 hereafter), we analyzed high signal-to-noise ratio occultations observed in 2012 and 2013, and derived stringent constraints on Pluto’s atmospheric profiles (density, pressure and temperature profiles), and on Pluto’s radius ($R_p = 1190 \pm 5$ km, assuming no troposphere). We also found a pressure increase of 6 ± 1% between 2012 and 2013.

Here we analyze a stellar occultation, observed on 2015 June 29 from Australia and New Zealand, which occurred two weeks before the NASA New Horizons (NH hereafter) flyby of the Pluto system. Our goals are: (1) assess further pressure changes between 2013 and 2015 (eventually providing useful constraints on Pluto’s seasonal models); (2) analyze the central flash that was detected for the first time ever from multiple stations. It constrains the thermal structure of a layer immediately above Pluto’s surface, its possible departure from sphericity and/or presence of hazes; and (3) constrain the pressure at Pluto’s surface. Besides serving as a useful comparison with the NH results, our work is one more benchmark in the long-term survey of Pluto’s atmosphere over the forthcoming years.

2. THE 2015 JUNE 29 OCCULTATION

The prediction procedures are described in DO15, Assafin et al. (2010), and Benedetti-Rossi et al. (2014). The event was monitored from Australia and New Zealand (Table 1), from which we obtained eight occultation detections. The reconstructed occultation geometry is displayed in Figure 1, see also Table 2. The light curves were obtained from classical aperture photometry, after correction of low frequency variations (caused by changing sky conditions) by means of nearby reference stars, when available. The resulting light curves $\phi(t)$ give the total flux from the star and Pluto’s system, normalized to unity outside the occultation, as a function of time $t$ (Figure 2). The observed flux $\phi$ can be written:

$$\phi = (1 - \phi_p) \cdot F_s + \phi_p,$$

where $F_s$ is the (useful) stellar flux alone, normalized between zero and unity. Thus, $\phi_p$ and $1 - \phi_p$ are the contributions of Pluto’s system and the unocculted stellar flux to $\phi$, respectively.

The quantity $\phi_p$ is in principle measured independently when Pluto and the occulted star are angularly resolved, providing $F_s$. It is difficult in practice and requires high photometric accuracy on the star, Pluto and nearby reference stars hours or days away from the event. During that time, sky and instrument conditions may vary. Moreover, for data taken without a filter (broadband), chromatic dependence of the extinction adds further systematic biases, especially if calibrations are not made at the same airmass.

One station that went deep into Pluto’s shadow (BOOTES-3, broadband, Castro-Tirado et al. 2012) obtained calibration images hours before the event, as the star and Pluto were marginally resolved. However, the overlap of the star and Pluto images prevents the useful determination of the Pluto/star ratio at the required accuracy (1% or better). Moreover the airmass variation (1.1 during calibration versus 1.6 during the occultation) introduces unmodeled chromatic effects due to color differences between the star and Pluto. More images taken the following night at very high airmass (3.6) do not provide further constraints on $\phi_p$.

One light curve (Dunedin) was affected by nonlinearity caused by a so-called “γ factor” (Poyntont 1997) that modified the pixel values to increase the image dynamical range. The (supposedly) reverse transformation provides an event that is globally not deep enough considering its duration, indicating residual nonlinearities. Thus, for this station, we only used the bottom part of the light curve (Figure 2), assuming that in this range, the retrieved flux $\phi$ is an affine function of the stellar flux, $\phi = a \cdot F_s + b$.

In spite of the lack of accurate measurements for $\phi_p$, the amplifying effect of the central flash still constrains the thermal structure of Pluto’s deepest atmospheric layers (see Section 4).

3. PRESSURE EVOLUTION

The DO15 model uses the simplest possible hypotheses, i.e., Pluto’s atmosphere (1) is pure nitrogen ($N_2$), (2) is spherically symmetric, (3) has a time-independent thermal structure, derived itself from the light curves, and (4) is transparent (haze-free). The validity of hypotheses (1)–(3) is discussed in DO15. Hypothesis (4) is discussed later in view of the NH results. Adjusting the pressure $p_0$ at a reference radius $r_0$ (for a given event) uniquely defines the molecular density profile $n(r)$, from which synthetic light curves are generated and compared to the data. Note that $p_0$ monitors the evolution of Pluto’s atmospheric pressure as a whole. In practice, most of the contribution to the fits comes from the half-light level ($F_s \sim 0.5$, $r \sim 1295$ km, $p \sim 1.7$ μbar), with a tapering off above $r \sim 1450$ km ($F_s \sim 0.9$, $p \sim 0.1$ μbar) and below $r \sim 1205$ km ($F_s \sim 0.1$, $p \sim 8$ μbar).

The parameters of our model are listed in Table 2 and our simultaneous fits are displayed in Figure 2. They have $\chi^2$ per degree of freedom close to unity, indicating satisfactory fits. Two minor modifications were introduced, relative to the DO15 model. First, we updated for consistency Pluto’s mass factor to $GM = 8.696 \times 10^{11}$ m$^3$ s$^{-2}$ (Stern et al. 2015), instead of $8.703 \times 10^{11}$ m$^3$ s$^{-2}$, causing negligible changes at our accuracy level. Second, we use the NH-derived Pluto radius ($R_p = 1187$ km) as a boundary condition for the DO15 model. This new value modifies (at a few percent level) the retrieved pressure at a given radius compared to DO15. Moreover, changing $R_p$ translates vertically all the profiles near the surface by an equivalent amount. In other words, all the quantities of interest (pressure, density, temperature) are well defined in terms of altitude above the surface, if not in absolute radius.
| Site                      | Lat. (d:m:s) | Lon. (d:m:s) | Telescope Exp. Time | Observers | Remarks                        |
|--------------------------|-------------|--------------|---------------------|-----------|--------------------------------|
| Melbourne Australia      | 37 50 38.50 S 145 14 24.40 E 110 | 0.20 m CCD/clear 0.32 | J. Milner | occultation detected          |
| Spring Hill Greenhill Obs. Australia | 42 25 51.55 S 147 17 15.49 E 650 | Harlingten/1.27 m EMCCD/B 0.32 | A. A. Cole, A. B. Giles K. M. Hill | occultation detected          |
| Blenheim1 New Zealand    | 41 32 08.59 S 173 57 25.09 E 18 | 0.28 m CCD/clear 0.64 | G. McKay | occultation detected          |
| Blenheim2 New Zealand    | 41 29 36.27 S 173 50 20.72 E 38 | 0.40 m CCD/clear 0.32 | W. H. Allen | occultation detected          |
| Martinborough New Zealand | 41 14 17.04 S 175 29 01.18 E 73 | 0.25 m CCD/B 0.16 | P. B. Graham | occultation detected          |
| Oxford New Zealand       | 43 18 36 S 172 13 08 E 66 | 0.35 m CCD/clear 1.28 | S. Parker | occultation detected, partially cloudy, not yet analyzed |
| Darfield New Zealand     | 43 28 52.90 S 172 06 24.04 E 210 | 0.25 m CCD/clear 0.32 | B. Loader | occultation detected, flash    |
| Christchurch New Zealand | 43 31 41 S 172 34 54 E 16 | 0.15 m CCD/clear 0.25 | R. Glassey | occultation detected, not yet analyzed |
| BOOTES-3 station Lauder New Zealand | 45 02 17.39 S 169 41 00.88 E 370 | Yock-Allen/0.6 m EMCCD/0.34 | M. Jelínek | occultation detected, flash    |
| Dunedin New Zealand      | 45 54 31. S 170 28 46. E 118 | 0.35 m CCD/clear 5.12 | A. Pennell, S. Todd M. Harnisch, R. Jansen | occultation detected, flash    |
| Glenlee Australia        | 23:16:09.6 S 150:30:00.8 E 50 | 0.30 m CCD/clear 0.32 | S. Kerr | no occultation detected        |
| Reedy Creek Australia    | 28 06 29.9 S 153 23 52.0 E 65 | 0.25 m CCD/clear 0.64 | J. Broughton | no occultation detected        |
| Linden Australia         | 33 42 30.9 S 150 29 43.5 E 583 | 0.76 m, 0.2 m CCD/clear 1.33, 1.28 | D. Gault, R. Horvat L. Davis | no occultation detected        |
| Leura Australia          | 33 43 09.0 S 150 20 53.9 E 903 m | 0.20 m visual n.a. | P. Nosworthy | no occultation detected        |
| Penrith Australia        | 33 45 43.31 S 150 44 30.30 E 96 | 0.62 m CCD/Clear 0.533 | D. Giles M. A. Barry | no occultation detected        |
| St Clair, Australia      | 33 48 37 S 150 46 37 E 41 | 0.35 m CCD/Clear 0.04 | H. Pavlov | no occultation detected        |
The pressures \( p_0 \) at \( r_0 = 1215 \) and 1275 km are given in Table 2. They are useful benchmarks, respectively corresponding to the stratopause (maximum temperature of 110 K), and the half-light level layer. Figure 3 displays the pressure evolution over 2012–2015. The formal error bars assume an invariant temperature profile, but this assumption should not affect the relative pressure changes in 2012–2015. Relaxing that constraint, we can retrieve \( p_0 \) by inverting individual light curves and testing the effects of the inversion parameters. This yields possible biases estimated to be \( \pm 0.2, \pm 0.8 \) and \( \pm 0.5 \) \( \mu \)bar in 2012, 2013 and 2015, respectively. We have added for comparison occultation results from 1988 (Yelle & Elliot 1997) and 2002 (Sicardy et al. 2003). They stem from different analyses and may also be affected by biases. However, Figure 3 should capture the main trend of Pluto’s atmosphere, i.e., a monotonic increase of pressure since 1988.

4. CENTRAL FLASH

Nearly diametric occultation light curves (but still avoiding the central flash) have flat bottoms (Figure 2). Our ray tracing code shows that near the shadow center, the stellar rays come from a “flash layer” about 3 km in thickness just above \( r = 1191 \) km, thus sitting 4 km on top of the assumed surface \( (R_p = 1187 \) km, Figure 3).

Let us denote by \( F \) a model for the stellar flux (distinguishing it from the observed flux \( F_\odot \)). Deep inside Pluto’s shadow, \( F \) is roughly proportional to the local density scale-height, \( H_n = -n/(dn/dr) = T/(\mu g/k + dT/dr) \), where \( \mu \) is the molecular weight, \( g \) is the acceleration of gravity and \( k \) is Boltzmann’s constant (DO15). For a spherical atmosphere, we have also \( F \propto 1/z \), where \( z \) is the distance to the shadow center. Writing \( z = \sqrt{\rho^2 + l^2} \), where \( \rho \) is the closest approach distance to the shadow center and \( l \) is the distance traveled from that point, we obtain:

\[
F \propto \frac{H_n}{z} = \frac{T}{\mu g/k + dT/dr} \cdot \left( \frac{1}{\sqrt{\rho^2 + l^2}} \right). \tag{2}
\]

For an approximately pure \( \text{N}_2 \) atmosphere (corresponding to \( \mu = 4.652 \times 10^{-26} \) kg), we obtain \( \mu g/k \sim 2 \) K km\(^{-1} \). As the thermal gradient \( dT/dr \) is several degrees per kilometer at the flash layer (see below), the flash amplitude is significantly controlled by \( dT/dr \).

Our best model minimizes the \( \chi^2 \) function defined by

\[
\chi^2 = \sum_i \frac{\phi_i - [(1 - \phi_p)F_i + \phi_p]}{\sigma_i^2},
\]

where \( \sigma_i^2 \) is the variance of \( \phi_i \) associated with the noise for the \( i \)th data point.

![Figure 1. Geometry of the 2015 June 29 Pluto stellar occultation. The stellar motion relative to Pluto (black arrow) is shown for seven stations, Me: Melbourne, Gr: Greenhill, Bl: Blenheim, Ma: Martinborough, Da: Darfield, Bo: BOOTES-3, Du: Dunedin. The J2000 celestial north and east are indicated by N and E, respectively. Pluto’s radius is fixed at 1187 km. The equator and prime meridian are drawn as thicker lines, and direction of rotation is along the gray arrow. The shaded region at center indicates the central flash zone.](image-url)
### Table 2
Input Parameters and Results

| Input Parameters | Star |
|------------------|------|
| Coordinates at epoch (J2000)\(^a\) | \(\alpha = 19^h 00^m 49^s 4801 \pm 11\) mas, \(\delta = -20^d 41^m 40^s 801 \pm 17\) mas |
| \(B, V, R, K\) magnitudes\(^b\) | 12.8, 12.2, 12.8, 10.6 |

| Pluto Parameters | |
|------------------|------|
| Pluto’s geocentric distance, shadow velocity\(^c\) | 4.77070 \(\times 10^6\) km, 24.1 km s\(^{-1}\) (at 16:53 UT) |
| Pluto’s mass and radius\(^d\) (Stern et al. 2015) | \(GM = 8.696 \times 10^{10}\) m\(^3\) s\(^{-2}\), \(R_p = 1187\) km |
| Sub-observer and sub-solar latitudes\(^d\) | \(B = +51^\circ 66, B' = +51^\circ 46\) |
| Pluto’s north pole position angle\(^d\) | \(P = +228^\circ 48\) |

### Results
Thermal Profile (Input Values for the DO15 Model)

| \(r_1, T_1, dT/dr (r_1), r_2, T_2\) | 1191.1 km, 81.7 K, 8.5 K km\(^{-1}\), 1217.3 km, 109.7 K |
| \(r_3, T_3, r_4, T_4\) | 1302.4 km, 95.5 K, 1392.0 km, 80.6 K |
| \(c1, c2, c3\) | \(1.42143317 \times 10^{-3}, 2.52794288 \times 10^{-3}, -2.12108557 \times 10^{-6}\) |
| \(c4, c5, c6\) | \(-4.88273258 \times 10^{-7}, -7.04714651 \times 10^{-8}, -3.3716945 \times 10^{4}\) |
| \(c7, c8, c9\) | \(7.7271133 \times 10^{-2}, -5.86944930 \times 10^{-2}, 1.48175559 \times 10^{-3}\) |

### Longitudes and Latitudes of Half-light Sub-occultation Points\(^e\)

#### Ingress

- Greenhill (154°E, 06°N, MT), Blenheim (120°E, 28°N, MT), Martinborough (119°E, 28°N, MT), Dunedin (108°E, 32°N, MT)
- Darfield (115°E, 30°N, MT), Bootes-3 (113°E, 31°N, MT), Dunedin (108°E, 32°N, MT)

#### Egress

- Greenhill (232°E, 37°S, MT), Blenheim (280°E, 35°S, ET), Martinborough (282°E, 34°S, ET), Dunedin (293°E, 31°S, ET), Darfield (286°E, 33°S, ET), Bootes-3 (288°E, 33°S, ET), Dunedin (293°E, 31°S, ET)

### Pressure (Quoted Errors at 1σ Level)\(^f\)

| Date | 2012 July 18 | 2013 May 04 | 2015 June 29 |
|------|------------|------------|------------|
| Pressure at 1215 km, \(p_{1215}\) | 6.07 ± 0.04 μbar | 6.61 ± 0.03 μbar | 6.94 ± 0.08 μbar |
| Pressure at 1275 km, \(p_{1275}\) | 2.09 ± 0.015 μbar | 2.27 ± 0.01 μbar | 2.39 ± 0.03 μbar |
| Surface pressure (Figure 3) | | 11.9 – 13.7 μbar |

### Astrometry

| Time of closest approach to shadow center (UT) | Closest approach to shadow center |
|-----------------------------------------------|---------------------------------|
| BOOTES-3: \(16^h 52^m 54.8 \pm 0.1\) | 4.59 ± 2 km N of shadow center |
| Dunedin: \(16^h 52^m 56.0 \pm 0.1\) | 44.6 ± 2 km S of shadow center |
| Geocenter: \(16^h 53^m 04.9 \pm 0.1\) | 3911.5 ± 2 km N of shadow center |

### Notes

\(^a\) See title’s footnote for information.

\(^b\) Zacharias et al. (2013), Cutri et al. (2003), Cutri (2012).

\(^c\) PLU043/DE433 ephemera.

\(^d\) Using Pluto’s north pole J2000 position: \(\alpha_p = 08^h 52^m 12594^s, \delta_p = -06^d 10^m 04^s 8^\prime\) (Tholen et al. 2008).

\(^e\) MT—morning terminator, ET—evening terminator.

\(^f\) Formal errors (except for the surface pressure). Possible systematic biases are ±0.2, ±0.8, and ±0.5 μbar in 2012, 2013, and 2015, respectively (Section 3).

Given model, it is convenient here (for sake of illustration) to note that \(F\) is essentially proportional to \(H_n\) (Equation (2)), so that \(\partial F/\partial H_n \sim F/H_n\). Detailed calculations show that at minimum \(\chi^2\), we have \(\partial^2 \chi^2/\partial H_n^2 = (2N/H_n^3)(\sigma_F^2/\sigma^2)\) for \(F \ll 1\), where \(\sigma_F^2 = F^2 - F^2\) is the variance of \(F\) (the bars denoting average values) and \(N\) is the number of data points.

Thus, the relative error on the scale-height is \(\delta H_n/H_n \sim (\sigma/\sigma_F)/\sqrt{N}\), which is small if the flash (and then \(\sigma_F\)) is large.

Since \(F\) increases as \(H_n\) increases or \(\rho\) decreases, \(H_n\) and \(\rho\) are correlated. However, the full width at half maximum (FWHM) of the flash is proportional to \(\rho\), while \(H_n\) controls homogeneously the flash amplitude, keeping its FWHM constant. This disentangles the effects of \(H_n\) and \(\rho\). More importantly, the BOOTES-3 and Dunedin stations exhibit flashes with similar amplitudes (Figure 2). This robustly forces the two stations to be symmetrically placed with respect to the
shadow center (Figure 1), thus imposing \( \rho \approx 45 \pm 2 \) km for both stations, independently of \( H_n \) (Table 2).

The \( \chi^2 \)-value is minimized for \( dT/dr = 8.5 \pm 0.25 \) K km\(^{-1} \) at 1191 km in our model. This particular value must be considered with caution, as it is not representative of the entire flash layer. Due to the functional dependence of \( T(r) \) (a branch of hyperbola, DO15), the gradient \( dT/dr \) varies rapidly around 1191 km. The average thermal gradient in the flash layer is in fact \( \sim 5 \) K km\(^{-1} \), consistent with a previous flash analysis (Olkin et al. 2014). Besides, it is typical of what is expected from the heating by methane (D. Strobel 2015, private communication). Other functional forms of \( T(r) \) could be tested, but this remains outside the scope of this paper. We note in passing that our best 2015 fit implies a residual stellar flux \( F_{\text{res}} = 0.028 \) (Figure 2) that is compatible with the possible range (0.010–0.031) mentioned earlier for 2012.

**Figure 2.** Simultaneous fits to our 2015 June 29 occultation light curves. The intervals under each name correspond to the time-span 16\(^{h}\) 52\(^{m}\)–16\(^{h}\) 53\(^{m}\) UT. The model is overplotted in blue, and the residuals are in gray. In the lower panels, the blue horizontal lines are the fitted values of Pluto’s contribution to the flux (\( \phi_p \), Equation (1)). The star symbol under the BOOTES-3 curve indicates a small flux deficit relative to the model. In the Dunedin panel, the smooth curve is the central flash at high resolution, before convolution by the exposure time (5.12 s), and vertically shifted for better viewing.
Our spherical, transparent atmospheric model essentially captures the correct shape and height of the central ash. It remains marginal, however, considering the general noise level. That said, it could be caused by an unmodeled departure of the flash layer from sphericity, but this is not anticipated. An atmosphere of radius $r$ rotating at angular velocity $\omega$ has an expected oblateness $\epsilon \sim r^3 \omega^2 / 2GM \sim 10^{-4}$ for a rotation period of 6.4 days, $r \sim 1190$ km and Pluto’s $GM$. Such oblateness causes a diamond-shaped caustic (Elliot et al. 1977) with a span of $4r \sigma < ~1$ km in the shadow plane. This is negligible considering the closest approach distances involved here (~45 km). Moreover, expected zonal winds of less than a few meters per second near 1191 km (Vangvichith 2013; Zalucha & Michaels 2013) would have even smaller effects. More complex distortions may arise, as varying thermal conditions along Pluto’s limb may slightly tilt the local iso-density layer, but its modeling remains outside the scope of this paper.

A possible explanation of the small discrepancy is that the primary and/or secondary stellar images hit topographic features while moving around Pluto’s limb. Curvature effects strongly stretch the images parallel to the limb during the central flash, by a ratio equal to the flash layer radius (1191 km) divided by the closest approach distance, about 45 km. From the star magnitudes (Table 2 and Kervella et al. 2004), we estimate its diameter as 33 $\mu$as, or 0.76 km projected at Pluto. The length of the stellar image is then $0.76 \times (1191/45) \sim 20$ km. It moves at about 4 km above the surface, which is comparable to the local topographic features reported from NH (Stern et al. 2015). It is thus possible that part of the stellar flux was partially blocked by mountains, causing the small observed drop. This can be tested by studying the topography derived from NH, noting that the primary and secondary stellar images at BOOTES-3 probed regions near longitude 190°E and latitude 20°S, and 10°E and 20°N, respectively, during the flash.

Finally, NH images reveal tenuous hazes with normal optical depth $\tau_N \sim 0.004$ and scale-height $H = 50$ km (Stern et al. 2015). This implies an optical depth along the line of sight of $\tau \sim \sqrt{2\pi r/H} \cdot \tau_N \sim 0.05$, which is indistinguishable from the noise level (Figure 2), supporting our transparent-atmosphere hypothesis.

5. SURFACE PRESSURE

Figure 3 displays our best pressure profile, with $p_{1191} = 11.0 \pm 0.2 \, \mu$bar at the deepest accessible level. To estimate the surface pressure, we need to extrapolate $p(r)$ into the blind zone. Two possible temperature profiles are considered, beside the DO15 model (Figure 3). One has a temperature gradient in the blind zone that tends to zero at the surface, where $p_{\text{surf}} = 13.0 \, \mu$bar and $T_{\text{surf}} = 36$ K. This describes a shallow troposphere that is in vapor pressure equilibrium with the surface, an example of a locally sublimating $N_2$ frost layer. The other profile has a constant gradient of 8.5 K km$^{-1}$, with $p_{\text{surf}} = 12.6 \, \mu$bar and $T_{\text{surf}} = 49$ K. Such warmer regions are indeed observed on Pluto (Lellouch et al. 2000), and they do not sublimate due to the absence of free $N_2$ frost. Considering the formal error bar $\pm 0.2 \, \mu$bar on $p_{1191}$, we obtain a range of 12.4–13.2 $\mu$bar for the surface pressure under hypotheses (1)–(4) of Section 3, and...
11.9–13.7 µbar accounting for the already discussed possible bias of ∼±0.5 µbar. Other thermal profiles could be considered at this point, but they would not change significantly our result due to the proximity (∼4 km) of our deepest accessible level to the surface, leaving little freedom for $p_{\text{surf}}$.

6. CONCLUSIONS

The 2015 June 29 stellar occultation provided a snapshot of Pluto’s atmosphere, after years of similar observations. Moreover, this was the first event with multi-chord cuts into the central flash. Assuming a spherical and transparent atmosphere as in DO15, we satisfactorily fit all the light curves, including the central flash part (Figure 2).

We find that Pluto’s atmospheric pressure has been increasing monotonically since 1988, with an augmentation of 5 ± 2% between 2013 and 2015, and an overall factor of almost three between 1988 and 2015 (Figure 3). This trend between 1988 and 2013 was confirmed by independent works by Elliot et al. (2003), Pasachoff et al. (2005), Person et al. (2013), Young (2013), Bosh et al. (2015). It is now extended to 2015 and rules out an ongoing atmospheric collapse associated with Pluto’s recession from the Sun. This is consistent with high thermal inertia models with a permanent N$_2$ ice cap over Pluto’s north pole, that preclude such collapse (Olkin et al. 2015). Other possible models where N$_2$ condenses on an unlit cap might announce a pressure decrease in the forthcoming years (Hansen et al. 2015). Further monitoring with occultations and a detailed analysis of the NH data will allow discrimination between those scenarios.

The central flash comes from a ∼3 km thick layer whose base is 4 km on top of Pluto’s surface. The amplitude of the flash is consistent with an average thermal gradient of ∼5 K km$^{-1}$ in that layer. Small departures from the model might be caused by topographic features along Pluto’s limb that block the stellar images.

Extrapolating possible temperature profiles down to the surface, we find a possible range of 11.9–13.7 µbar for the surface pressure. This is larger than, but compatible with the entry value 11 ± 1 µbar derived from the NH radio occultation experiment (Hinson et al. 2015; Gladstone et al. 2016). At this stage, more detailed investigations of both techniques should be undertaken to see if this difference is significant, or the result of unaccounted effects. In any case, the two techniques validate each other, an excellent prospect for future monitoring of Pluto’s atmosphere from ground-based occultations.

We acknowledge support from the French grant “Beyond Neptune II” ANR-11-IS56-0002, and Labex ESEP. The research leading to these results has received funding from the European Research Council under the European Community’s H2020 (2014–2020/ERC Grant Agreement 669416 “LUCKY STAR”). E.M. acknowledges support from the contrato de subvención 205–2014–Fondecyt, Peru. J.I.B.C. acknowledges the CNPq/PQ2 fellowship 308489/2013-6. M.A. acknowledges the FAPERJ grant 111.488/2013, CNPq/PQ2 fellowship 312394/2014-4, and grants 482080/2009-4 and 473002/2013-2. J.L.O. acknowledges funding from Proyecto de Excelencia de la Junta de Andalucía J. A. 2012-FQM1776, Spanish grant AYA-2014-56637-C2-1-P, and FEDER funds. A.J.C.T. acknowledges support from the Junta de Andalucía (Project P07-TIC-03094) and Univ. of Auckland and NIWA for installing of the Spanish BOOTES-3 station in New Zealand, and support from the Spanish Ministry Projects AYA2012-39727-C03-01 and 2015-71718R Development of the Greenhill Observatory was supported under the Australian Research Council’s LIEF funding scheme (project LE110100055). We thank C. Harlington for the use of the H127 Telescope, and D. and M. Warren for long term support. We thank L. Beauvalet for running the ODIN Pluto’s system model, M. W. Buie, S. Gwyn, and L. A. Young for providing pre-event Pluto’s ephemeris and astrometry, D. P. Hinson and D. F. Strobel for most useful discussions, and the reviewer for useful comments.

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