PLUTO’S ATMOSPHERE FROM STELLAR OCCULTATIONS IN 2012 AND 2013

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A., Dumas, C., Emilio, M., Fabrega Polleri, J., Gil-Hutton, R., Gillon, M., Girard, J., Hau, G. K.
T., Ivanov, V. D., Jehin, E., Lecacheux, J., Leiva, R. Lopez-Sisterna, C., Mancini, L., Manfroid, J.,
Maury, A., Meza, E., Morales, N., Nagy, L., Opitom, C., Ortiz, J. L., Pollock, J., Roques, F.,
Summary

- Introduction
- Events (Prediction, Observation and Calibration)
- Modeling
- General atmospheric structure
- Stratosphere
- Mesosphere negative temperature gradient
- Conclusions
Why study Pluto’s atmosphere?

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- Atmospheric structure - Correct interpretation of observational data (spectra).
- Appearance and maintenance of atmospheres - Other trans-neptunian objects with size and surface gravity comparable to those of Pluto within a factor of two, exhibited none atmosphere at the 10 nbar pressure level.
How to study it?

- **Direct Observation** - Spectroscopy. Information about the atmosphere and surface chemical composition, and surface temperature.
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- **Direct Observation** - Spectroscopy. Information about the atmosphere and surface chemical composition, and surface temperature.
- **Indirect Observation** - Stellar occultations. High precision density, pressure and temperature profiles. Gravity waves (turbulence). Surface radius and composition (Combined with spectroscopy information).
Stellar Occultations

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- As far as ground based observations are concern, it is the most effective technique available to study Pluto’s atmosphere. It allows an atmospheric probe to nbar levels (Sicardy et al., 2011; Olkin et al., 2014).
Stellar Occultations

- Responsible for Pluto’s atmosphere discovery (Hubbard et al., 1988; Elliot et al., 1989; Brosch, 1995).
Prediction

- Prediction catalog - Assafin et al. (2010) Observed Pluto’s path in the sky plane between 2008 and 2015, performed at ESO’s 2.2 m telescope.
Prediction

- Predicted events observed at South America with ESO’s 8.2 m VLT, among others.

July 18, 2012 - R* 14

May 4, 2013 - R* 13.7
Observation


Observation

- São Pedro de Atacama
- La Silla
- TRAPPIST
- DANISH
- Cerro Tololo
- Pico dos Dias
- Paranal - VLT/ESO
- Cerro Burek
- Pico dos Dias
Calibration

- Digital coronography for calibration.
Calibration

- Stellar residual flux varied from 2.3 % to 1.8 % of its unocculted value.
General Idea

- Assuming a layer model, a incident light ray suffers successives refractions, curving in the atmosphere until emerge.

![Diagram of light ray in atmosphere](image)
General Idea

\[ I(r_0) = \eta(r) \cdot r \cdot \text{sen} \theta \]
General Model

- Total deviation $\omega(r_0)$ is (Vapillon et al., 1973):

$$\omega(I_0) = \int_{r_0}^{\infty} \frac{2I_0}{\eta(r)} \cdot \frac{d\eta(r)}{dr} \cdot \frac{dr}{\sqrt[2]{[\eta(r) \cdot r]^2 - [\eta(r_0) \cdot r_0]^2}}$$ (1)
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- Inverting for $\eta(r_0)$:

$$\eta(r_0) = \exp \left\{ \frac{1}{\pi} \int_{\omega(I_0)}^{0} \log \left[ \frac{l(\omega)}{l_0} + \sqrt{\left( \frac{l(\omega)}{l_0} \right)^2 - 1} \right] \cdot d\omega \right\} \quad (2)$$
For small $\omega(r_0)$:

$$z(t) = I(t) + D \cdot \omega(t)$$  (3)
General Model

By energy conservation we can write:

\[
\frac{\Phi(t)}{\Phi_0} = \frac{dl(t)}{dz(t)}
\]  

(4)
General Model

\[
\frac{\Phi(t)}{\Phi_0} = f \cdot \frac{dl(t)}{dz(t)} \text{ where } f = \frac{l(t)}{z(t)}
\]  
(5)

\[
\omega(t) = \frac{1}{D} \cdot \int_{-\infty}^{t} \frac{f \cdot \Phi_0 - \Phi(\tau)}{f \cdot \Phi_0} \cdot \frac{dz}{d\tau} d\tau
\]  
(6)
Reduction Approaches

Inversion:

- From the event data \( \Phi(t)/\Phi_0 \) and \( z(t) \), we calculate \( I(t) e^{\omega(t)} \).
Reduction Approaches

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- From the event data ($\Phi(t)/\Phi_0$ and $z(t)$), we calculate $I(t)$ e $\omega(t)$.
- From general model (Vapillon et al., 1973), we use $I(t)$ and $\omega(t)$ to get $\eta(r)$.
Reduction Approaches

Inversion:

- From the event data \(\Phi(t)/\Phi_0\) and \(z(t)\), we calculate \(I(t)\) and \(\omega(t)\).
- From general model (Vapillon et al., 1973), we use \(I(t)\) and \(\omega(t)\) to get \(\eta(r)\).
- From \(\eta(r)\), we use a atmospheric model (assumptions) to determine \(T(r)\), \(n(r)\) and \(P(r)\).
General Idea

*Ray Tracing:*

- From an atmospheric model \((T(r), n(r) e P(r))\) we calculate \(\eta(r)\).
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- From an atmospheric model \((T(r), n(r), e P(r))\) we calculate \(\eta(r)\).
- Using \(\eta(r)\) and the general model, we have \(\omega(l_0)\) for each \(l(t)\).
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- From an atmospheric model \((T(r), n(r) \text{ e } P(r))\) we calculate \(\eta(r)\).
- Using \(\eta(r)\) and the general model, we have \(\omega(I_0)\) for each \(I(t)\).
- From values of \(I(t)\) and \(\omega(t)\) we calculate synthetic values for \(\Phi(t)/\Phi_0\) and \(z(t)\).
Simplifying assumptions

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where

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- $T(r)$ is time-independent, i.e. the temperature profiles are the same in 2012 and 2013.
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- With new shadow’s center coordinates, the inversion of the best light-curve is performed again and the procedures is resumed.
Combining the data

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- Using the calculated $r_i$, we redo the ray tracing for the July 18, 2012 event to determine $P_i$ and the shadows center coordinates.
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- Using the calculated $r_i$, we redo the ray tracing for the July 18, 2012 event to determine $P_i$ and the shadows center coordinates.
- We new center coordinates ($z(t)$) we redo July 18, 2012 event inversion to get a precise temperature profile.
Parametrization of $T(r)$
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\[
\begin{align*}
T(r) &= T_1 + \frac{dT}{dr} \cdot (r - r_1), & r \leq r_2 \\
C_1 \cdot r + C_2 \cdot T(r) + C_3 \cdot r \cdot T(r) + C_4 \cdot r^2 + C_5 \cdot T(r)^2 &= 1, & r_2 \leq r \leq r_4 \\
T(r) &= C_6 + C_7 \cdot r + C_8 \cdot r^2 + C_9 \cdot r^3, & r_4 \leq r \leq r_5 \\
T(r) &= T_{iso} & r \geq r_5
\end{align*}
\]
General atmospheric structure

## Final Temperature Profile

<table>
<thead>
<tr>
<th>Physical parameters</th>
<th>( 8.703 \times 10^{11} \text{ m}^3 \text{ s}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pluto’s mass(^1)</td>
<td>( 4.652 \times 10^{-26} \text{ kg} )</td>
</tr>
<tr>
<td>Nitrogen molecular mass(^2)</td>
<td>( K = 1.091 \times 10^{-23} + (6.282 \times 10^{-26} / \lambda_{\mu m}^2) \text{ cm}^3 \text{ molecule}^{-1} )</td>
</tr>
<tr>
<td>Nitrogen molecular refractivity(^3)</td>
<td>( k = 1.380626 \times 10^{-23} \text{ J K}^{-1} )</td>
</tr>
</tbody>
</table>

| The nine free parameters of the best temperature profile\(^4\) |
|------------------|---------------------------------|
| \( r_1, T_1, dT/dr(r_1) \) | 1,190.4 ± 1 km, 36 K, 16.9 K km\(^{-1}\) |
| \( r_2, T_2 \) | 1,217.3 km, 109.7 K |
| \( r_3, T_3 \) | 1,302.4 km, 95.5 K (implying \( dT/dr(r_3) = -0.206 \text{ K km}^{-1} \)) |
| \( r_4, T_4 \) | 1,392.0 km, 80.6 K |
| \( c_{1}, c_{2} \) | \( 1.41397736 \times 10^{-3}, 2.59861886 \times 10^{-3} \) |
| \( c_{3}, c_{4} \) | \( -2.19756021 \times 10^{-6}, -4.81764971 \times 10^{-7} \) |
| \( c_{5}, c_{6} \) | \( 8.66619700 \times 10^{-8}, -3.6213609 \times 10^{4} \) |
| \( c_{7}, c_{8} \) | \( 8.2775269 \times 10^{1}, -6.27372563 \times 10^{-2} \) |
| \( c_{9} \) | \( 1.58068760 \times 10^{-5} \) |

| The three free parameters particular to each event\(^5\) |
|------------------|-------------------|
| 18 July 2012     | 04 May 2013       |
| Pressure at \( r = 1,275 \text{ km}, p_{1,275} \) | \( 2.16 ± 0.02 \text{ μbar} \) \( 2.30 ± 0.01 \text{ μbar} \) |
| Time of closest geocentric approach | \( 04:13:37.24±0.07 \text{ UT} \) \( 08:22:27.11±0.09 \text{ UT} \) |
| Distance of closest geocentric approach\(^6\) | \( -404.6 ± 2.7 \text{ km} \) \( -723.5 ± 2.7 \text{ km} \) |
Final Temperature Profile
Fitted Light-curves

04:13 UT

18 July 2012

Santa Martina

Cerro Burek

Paranal

San Pedro de Atacama

Huancayo

Normalized Flux

Time

Iso.

$\chi^2_{\text{dof}} = 1.19$

$\chi^2_{\text{dof}} = 0.945$

$\chi^2_{\text{dof}} = 2.75$

$\chi^2_{\text{dof}} = 1.58$

$\chi^2_{\text{dof}} = 1.17$
Fitted Light-curves

08:22 UT

Normalized Flux

Time
Radius determination

\[ r (\text{km}) \]

\[ T (\text{K}) \]

\[ 1190 \pm 5 \text{ km} \]
Possible cooling by CO or HCN
Conclusions

Combination of well-sampled occultation chords and high SNR data, have allowed us to constrain the density, temperature and thermal gradient profiles of Pluto’s atmosphere, between radii $r \sim 1,190$ km (pressure $p \sim 11$ µbar) and $r \sim 1,450$ km (pressure $p \sim 0.1$ µbar).

We find that a unique thermal model, cannot satisfactorily fit twelve light-curves observed in 2012 and 2013, assuming a spherically symmetric and clear (no haze) atmosphere.
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- We find that a unique thermal model, can fit satisfactorily twelve light-curves observed in 2012 and 2013, assuming a spherically symmetric and clear (no haze) atmosphere.
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- The absolute vertical scale of our global model has an internal accuracy of about ±1 km. However, this error is amplified to ±5 km at the bottom of the profiles, because of the uncertainty on the residual stellar flux in the central part of the occultation observed by NACO on 18 July 2012.
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- In the frame of our model (i.e. assuming a constant temperature profile), we detect a significant 6% pressure increase (at the 6-$\sigma$ level), during the $\sim 9.5$ months separating the two events under study. This means that Pluto’s atmosphere was still expanding at that time, confirming the work of Olkin et al. (2015), which compiles and analyzes pressure measurements between 1988 and 2013.
Conclusions

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- From a Pluto’s mass of $M_P = 1.304 \pm 0.006 \times 10^{22}$ kg (Tholen et al., 2008), we derive a density $\rho_P = (1.802 \pm 0.007)(R_P/1,200 \text{ km})^{-3}$ g cm$^{-3}$. Our estimation thus implies $\rho_P = 1.85 \pm 0.02$ g cm$^{-3}$. This is larger, but not by much, than Charon’s density, $\rho_C = 1.63 \pm 0.05$ g cm$^{-3}$. 
Conclusions

- Above the stratopause, and up to about 1,390 km, our best 2012 and 2013 occultation light-curves yield inverted temperature profiles with a negative thermal gradient close to -0.2 K km$^{-1}$, which amounts to a total decrease of 30 K for the temperature between 1,215 and 1,390 km.
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- Explaining this negative gradient by CO cooling requires a mixing ratio \((200 \times 10^{-4})\), that is too high by a factor of 40 compared to current measurements (Lellouch et al., 2011). Cooling by HCN is also discussed in this paper. It appears to be a possible alternative solution, but only if it remains largely supersaturated in the mesosphere.
Conclusions

- The *New Horizons* flyby data will provide constraints on the temperature boundary conditions and atmospheric composition that will be used to discriminate between the various solutions described here.


Lellouch, E., Stansberry, J., Emery, J., Grundy, W., Cruikshank, D.P., 2011. Thermal properties of Pluto’s
Charon’s surfaces from Spitzer observations. Icarus 214, 701–716.


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