What Titan’s phase curves can teach us about exoplanet atmospheres

A. García Muñoz
Technische Universität Berlin, Berlin, Germany

Collaborators:

P. Lavvas (U. Reims, France), R.A. West (JPL, US)
&
J. Cabrera (DLR Berlin, Germany)
Phase curves

Shape is VERY informative!!

Out-of-eclipse phases

A_g @ full illumination

Planet-star brightness

Orbital phase

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A classical problem in solar system science

E.g.: Venus, Mercury, Titan

- Phase curve shape $\rightarrow$ atmospheric optical properties.
- Reflected sunlight $\rightarrow$ Energy budget.

...which is highly relevant for exoplanets.

- We use solar system objects as benchmarks & motivation.
- In this exercise, we learn about Titan too!
Our work — Cassini Imaging Science Subsystem

Images:

- Total of ~6,000
- 12 years: 2004 — 2015
- 15 filters: 300 nm —> 940 nm
- Phase angles: 0 —> 165°
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Phase angle $\alpha$ (°)

- Filter = UV2_CL2 $\lambda_{eff} = 306$ nm
  - $\sigma = 6.9\%$ $\omega_{0g} = 1.000$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 12.08$
  - $A_g \Phi (\alpha = 0) = 0.045$
  - $q = 2.84$

- Filter = CL1_UV3 $\lambda_{eff} = 343$ nm
  - $\sigma = 6.4\%$ $\omega_{0g} = 1.000$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 10.90$
  - $A_g \Phi (\alpha = 0) = 0.059$
  - $q = 2.66$

- Filter = CL1_BL2 $\lambda_{eff} = 441$ nm
  - $\sigma = 13.7\%$ $\omega_{0g} = 1.000$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 4.89$
  - $A_g \Phi (\alpha = 0) = 0.128$
  - $q = 1.92$

- Filter = CL1_CL2 $\lambda_{eff} = 455$ nm
  - $\sigma = 6.4\%$ $\omega_{0g} = 1.000$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 4.52$
  - $A_g \Phi (\alpha = 0) = 0.136$
  - $q = 1.97$

- Filter = CL1_GRN $\lambda_{eff} = 569$ nm
  - $\sigma = 4.6\%$ $\omega_{0g} = 1.000$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 3.41$
  - $A_g \Phi (\alpha = 0) = 0.227$
  - $q = 1.97$

- Filter = CL1_MT1 $\lambda_{eff} = 619$ nm
  - $\sigma = 3.9\%$ $\omega_{0g} = 0.575$
  - $A_g \Phi (a \rightarrow 180^\circ) \rightarrow 3.28$
  - $A_g \Phi (\alpha = 0) = 0.224$
  - $q = 2.04$
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Diagnostics possibilities

\[ \alpha < 165^\circ \]

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What’s special with Titan

- **Puffy** atmosphere, $H_a/R_T \sim 0.015 >>$ other solar system planets
- **Hazy** atmosphere.
- (Photochemical) haze is strongly **forward scattering** ($r_{\text{eff}} \sim 3 \, \mu m$).

Interpretation:

- Forward scattering of whole moon.
- Excellent match of model (**red**) and observations (**black symbols**)... Reliable prediction based on DISR aerosol properties...
Brightness at large phase angles significantly exceeds brightness at full illumination.

$$A_g\Phi(\alpha=180) \sim 10-200 \ A_g\Phi(0)$$
**Diagnostics. Theory.**

- *Exponential atmosphere*, scale height $H_g = kT/\mu g$.
- Haze distributed vertically with $H_a = H_g$.
- Haze particles of prescribed size $r_{\text{eff}}$.
- Single scattering dominates scattered signal.

Planet-to-star contrast at $\alpha = 180^\circ$:

$$\frac{F_p}{F_\star} = \frac{1}{a^2} \times 2\pi H_a R_p \times p_a(\theta = 0) \overline{\omega}_{0,a}$$

Sensitive to haze size

Microphysical models are needed!!

Area of ring
**Brightness surge occurs ONLY when:**

- Atmosphere is puffy, $H_a/R_p \sim 0.01$ or more.
  
  **AND**

- $p_a(\theta=0)$ is large ($\rightarrow$ large haze particles).

**Inversely:**

Detection of brightness surge will impose joint constraint on $H_a/R_p$ $p_a(\theta=0)$

**At exoplanets?**
Considerations (I):

- Inflated (~puffy) exoplanets do exist —> large $H_a/R_p$.
- Hazy atmospheres. Plenty of them!

- Estimating $p_a(\theta=0)$ (particle size) is very uncertain.

\[
\frac{F_p}{F_\star} = \frac{1}{a^2} \times 2\pi H_a R_p \times p_a(\theta = 0) \varpi_{0,a}
\]

\[
\frac{H_a}{R_p} \propto \frac{kT_{eq}}{GM_p/R_p}
\]

\[
T_{eq} = T_{eff}(R_\star/2a)^{1/2}
\]
Considerations (II):

\[
\frac{F_p}{F_*} = \frac{1}{a^2} \times 2\pi H_a R_p \times p_a(\theta = 0) \varpi_{0,a}
\]

For very close-in planets, star is not point like!
Finite angular size must be taken into account

\[p_a(\theta) \text{ and } <p_a(\Theta)> \text{ may differ by orders of magnitude}
\]

\[\rightarrow \rightarrow \rightarrow \rightarrow\]

stronger signal out of transit
Contrast at $\alpha = 180^\circ$

If $r_{\text{eff}} \sim 1\mu m \rightarrow F_p/F_s > 10^{-20}\text{ppm}$
CoRoT-24 b & other super-puffy Neptunes  
(Lammer et al. 2016)

- Much more puffy than Titan, $H/R_T \sim 0.035 > 0.015$ of Titan
- Occultation. If $A_g \sim 0.3 \rightarrow F_p/F_s(\alpha=0) \sim 2.3$ ppm

Forward scattering:
- If $r_{\text{eff}} \sim 1-2 \mu m \rightarrow F_p/F_s(\alpha=170–175^\circ) \sim 10$ ppm

*These objects would be easier to characterize in forward scattering than in occultation.*

*...if they occur around bright stars...*
What Titan’s phase curves can teach us about exoplanet atmospheres

- **Phase curves contain valuable diagnostics information**

- **At large phase angles:**
  
  *info on aerosol stratification and particle sizes*

- Non-detection of forward scattering sets a constraint.

- A way to probe puffy Neptunes?

- Real phase curves are **NOT** Lambertian. This should be a conclusion, not an assumption.

- Forward scattering has impact on:
  
  - Scattering of energy, phase integral $q \sim 3 > 1.5$ (Lambertian)
  
  - $M_p$ determination from Doppler-Ellipsoidal fitting.