Exploring the Solar System using stellar occultations

Bruno Sicardy (UPMC & Paris Obs.)
Nicolle Rager Fuller, in https://www.sciencenews.org/article/voyagers-view
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Morbidelli & Levison, Nature 2003
What is a stellar occultation? → A body hides a star as it moves in the sky, e.g., here the Centaur object Chariklo.
the object is *not* resolved

temporal resolution equivalent to < 1km
Occultation detection of a neptunian ring-like arc

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The apparent closest approach of the star SAO186001 to Neptune was observed photoelectrically on 22 July 1984 at Cerro Tololo Inter-American Observatory. A 32% signal drop lasting about 1.2 s was probably caused by a partially transparent arc of material at a distance of 67,000 km from Neptune. Neptune’s arc(s) do not vary smoothly with azimuth, unlike the rings of other jovian planets.
Neptune occultation
CFHT
3.6-m telescope
2.2 μm
20 August 1985
Sicardy 1987
typical uncertainty in the 1980’s ~ 0.5 arcsec
Pluto at **best** HST resolution details ~ 500 km at best

Earth's Moon at the same resolution

**Occultations:** highly efficient method

http://pluto.jhuapl.edu/Participate/community/What-We-Know.php?link=Making-Maps
Pluto at **best** HST resolution details ~ 500 km at best

Earth's Moon at the same resolution

**Occultations**: highly efficient method

spatial resolution ~ fraction of km
Pluto at **best** HST resolution details \(\sim 500\) km at best

Earth's Moon at the same resolution

**Occultations**: highly efficient method

spatial resolution \(\sim\) fraction of km

sensitivity to atmosphere \(\sim\) a few nanobars
collaborative science with professional and amateur astronomers

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Les plus grands objets transneptuniens connus

- Kerberos?
- Charon
- Chariklo
- Pluton
- Éris
- 2007 UK\textsubscript{126}
- 2002 VE\textsubscript{95}
- Asbolus
- Makemake
- 2003 VS2
- Ixion
- Sedna
- Orcus
- 2002 KX\textsubscript{14}
- Quaoar
- 2005 TV\textsubscript{189}
- Varuna
- 2002 TX\textsubscript{300}
- 2003 AZ\textsubscript{84}
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Chariklo occultation
Namibia April 9, 2017

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Pluto occultation
Mt John, New Zealand
June 2006
Quaoar, a dwarf planet beyond Pluto (58s occultation)
Antiope occultation
Kelly Beatty Sky & Telescope
9 Sept. 2011

from F. Colas, F. Marchis with US and European amateurs

www.skyandtelescope.com/astronomy-news/observing-news/
antiope-occultation-yields-double-bonanza/
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we need **three** orders of magnitude improvement
Pluto

Charon

Titan

Eris

Makemake

quaoar

a stamp viewed at 150 km

$10^{-7}$ radian

$\sim 20$ mas $\rightarrow$

very small !!
Charon occultation, Paranal, Chile
July 2005

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an example: Pluto’s atmosphere
August 21, 2002 Pluto occultation:
reconstruction of what happened

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August 21, 2002 Pluto occultation: reconstruction of what happened

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The July 19, 2016 Pluto occultation
our prediction as of early July

green dots: sites involved in the campaign (not all got data!)
The prediction using the GAIA “DR0” catalog (one star!) + the New Horizons-updated ephemeris

green dots: sites involved in the campaign (not all got data!)
The July 19, 2016 Pluto occultation

post-occultation reconstructed path (what really happened)

shadow center
shadow
northern limit

shadow

shadow
southern limit

green dots: sites involved in the campaign (not all got data!)

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The Pluto July 19, 2016 stellar occultation

Valle d’Aosta
T81 cm
Italy

Wise Observatory
T70 cm
Israel

Telecopio Nazionale Galileo
T358 cm
Italy/La Palma

Pic du Midi
T100 cm
France

Flux (star + Pluto)

Time

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The Pluto July 19, 2016 stellar occultation

- Valle d’Aosta, T81 cm, Italy
- Wise Observatory, T70 cm, Israel
- Telecopio Nazionale Galileo, T358 cm, Italy/La Palma
- Pic du Midi, T100 cm, France

Flux (star + Pluto)

Time

2 min

residuals

blue= simultaneous fit to the data using a Pluton atmospheric model

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very tenuous atmosphere (few µbar) \( \rightarrow \) in vapor pressure equilibrium with surface

\( \text{N}_2 \) condensation

\( \text{N}_2 \) sublimation
Year
Pressure at 1215 km (µbar)

1990 2000 2010 2020

0 2 4 6 8

Yelle & Elliot (1997)
Sicardy et al. (2003)
Dias Oliveira et al. (2015)
Sicardy et al. (2016)

NH flyby
paradoxical increase of pressure (factor ~ 2.8) but ~ 24% decrease of insolation in 22 years
Pluto’s atmosphere confounds researchers
Kelly Beatty, Sky & Telescope 25 March 2016

www.skyandtelescope.com/astronomy-news/plutos-atmosphere-confounds-researchers-032520166
Gaia allows to make “meteorology” of Pluto’s atmosphere

~120 mas

winter hemisphere

Spunik planum

summer hemisphere
central flashes
Pluto 29 June 2015 occultation
flight of the NASA plane SOFIA to catch Pluto central flash on June 29, 2015 (MIT team)

flight path adjusted in “real time” from astrometric updates

tweaking to get into central line at the right time
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micro-lensing phenomenon "Einstein arcs"

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The micro-lensing phenomenon, known as "Einstein arcs," is illustrated in the diagram. For Pluto, the observer must go < 50 km from the center, approximately 2 mas. The diagram shows the primary and secondary images, with the source and primary image indicated. 

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Titan occultation
Namibia
November 2003

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2.2 \(\mu m\)

same place, strong chromatic effect!

0.89 \(\mu m\)
central flash from a *spherical* and *transparent* atmosphere!

discovery of rings
...first rings ever discovered around a body other than a giant planet

- Jupiter: 1979
- Saturn: 1610
- Uranus: 1977 (occultation)
- Neptune: 1984 (occultation)
- Chariklo: 2013 (occultation)

(not on scale!)

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A ring system detected around the Centaur (10199) Chariklo on June 3, 2013

20 seconds that changed our conception of rings...

Danish 154cm-telescope, La silla, Chile

Braga-Ribas et al. 2014
no diffuse rings detected
\( \tau < \sim 0.01 \) on large scale

Danish Telescope
3 June 2013
observers:
C. Snodgrass et al.
an extra-ordinary object:
first planetary rings ever observed
outside giant planets

an artist view... credit ESO
an extra-ordinary object: first planetary rings ever observed outside giant planets
a **montage** comparing Chariklo and Pluto
Chariklo’s ephemeris, a bootstrapping approach using GAIA

see the talk by Josselin Desmars (next session) and poster by Julio Camargo
The Chariklo occultation of April 9, 2017, Namibia
Mike Kretlow
the Chariklo
occultation of April 9, 2017
Weavers Rocks « m2 » 50-cm © jean-Luc Dauvergne

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The occultation by Chariklon, Namibia April 9, 2017

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Flux

C1R  C2R

Radius in ring plane (km)

June 3, 2013
Danish

April 29, 2014
Springbok
Gifberg

April 29, 2014
SAAO

Sicardy et al. 2017
$m=1$ (e.g. Uranus $\epsilon$ ring) \hspace{2cm} m=2$ (e.g. Uranus $\delta$ ring)

$\Omega_{m=1} \sim \hat{\omega}$

$\Omega_{m=2} \sim n/2$

pattern speeds:

$\sim 80$ mas
Formation of rings around Saturn’s moon Iapetus
Iapetus equatorial ridge

20 km ~ 2 mas at Charilklo’s distance

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Cassini image
Iapetus equatorial ridge

mobile stations

Cassini image
Chariklo+rings occultation, July 23 2017
improved NIMA 11 ephem. + pre-release of DR2 Gaia star position

by: LuckyStar

d m year h:m:s UT ra___dec___J2000___candidate C/A P/A vel Delta G* J* long
23 07 2017 05 58 52. 18 48 09.2214 -31 26 32.6400 0.031 6.94 -21.01 14.72 14.0 12.4 -109.
the Triton occultation of October 5, 2017

central flash typically ~ 100 km

http://lesia.obspm.fr/lucky-star/predictions/
thank you!

http://lesia.obspm.fr/lucky-star/predictions/

 Predictions of stellar occultations by TNOs and Centaurs in 2017

**ERC Project Lucky Star**

This page presents the prediction of occultations by selected TNOs and Centaurs for 2017. These predictions are made in the framework of Lucky Star project (led by B. Sicardy) and in collaboration with groups from Paris, Meudon, Granada and Rio. Information about the predictions can be found in Assafin et al. (2010) for Pluto system predictions, Assafin et al. (2012) for the TNO predictions, Camargo et al. (2014) for TNO and Centaur predictions. Ephemerides of the selected objects come from Desmars et al. (2015) and they are regularly updated thanks to observations from Minor Planet Center and our own observations made at ESO, Pic du Midi, Calar Alto, Sierra Nevada and Observatorio do Pico dos Dias. Predictions make use of Gaia DR1 (Gaia Collaboration, 2016) for the positions of stars.

For three very specific occultations occurring this year, the Gaia team has provided position, proper motion and parallax for the three occulted stars with the preliminary Gaia Data Release 2. The events are for Charliko on 22 June 2017 and 23 July 2017, and for Triton on 5 October 2017.

**IMPORTANT:** If you plan to observe one of these predicted events, please contact J. Desmars.

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**Predictions for 2018 →**

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**Occultation circumstances**

<table>
<thead>
<tr>
<th>Object</th>
<th>[NGO] Charliko</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2017-07-23 03:58:32</td>
</tr>
<tr>
<td>Star position</td>
<td>18 48 09.2214 -31 26 32.460</td>
</tr>
<tr>
<td>Stellar catalogue</td>
<td>preliminary Gaia DR2</td>
</tr>
<tr>
<td>Proper motion</td>
<td>μRA=-4.623 mas/yr, μDec=6.228 mas/yr</td>
</tr>
<tr>
<td>Object position</td>
<td>18 48 09.2133 -31 26 32.413</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>HMAST17</td>
</tr>
<tr>
<td>C/A</td>
<td>0.031</td>
</tr>
<tr>
<td>P/A</td>
<td>6.94</td>
</tr>
<tr>
<td>velocity (km/s)</td>
<td>21.014</td>
</tr>
<tr>
<td>Geocentric distance A (au)</td>
<td>14.723</td>
</tr>
<tr>
<td>G mag*</td>
<td>14.0</td>
</tr>
<tr>
<td>J mag*</td>
<td>12.4</td>
</tr>
</tbody>
</table>

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