The Chariklo Occultation Campaign 2017

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IOTA - ES & Lucky Star Project
ESOP 36, Freiberg, Germany, 2017 Sep 15-17
(10199) Chariklo

Largest known Centaur (D ~260 km)

Centaurs are objects from the Kuiper belt.

- Having perturbed inward by Neptune and/or Uranus.
- Dynamically (long-term-) unstable orbits.
- Will be ejected from SS, impact (planet, Sun) or change into short-period comet.
Gestreute Kuipergürtelobjekte

Transneptunische Objekte
q = 13.1 au, Q = 18.5 au, e = 0.172, i = 23.4°, P = 62.9 yrs
Solar System View (2017-06-22)

q = 13.1 au, Q = 18.5 au, e = 0.172, i = 23.4°, P = 62.9 yrs
Chariklo Skymap (2017-06-22)

δ -32°

Pluto (14.2m)

(10199) Chariklo (18.5m, Zentaur)

Saturn (0.0m)

Schütze

Süder
Table 7. Physical parameters of Chariklo from stellar occultations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sphere</th>
<th>Maclaurin</th>
<th>Ellipsoid</th>
<th>Jacobi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (kg m$^{-3}$)</td>
<td>...</td>
<td>$970^{+300}_{-180}$</td>
<td>...</td>
<td>$796^{+2}_{-4}$</td>
</tr>
<tr>
<td>a (km)</td>
<td>129 ± 3</td>
<td>$143^{+3}_{-6}$</td>
<td>$148^{+6}_{-4}$</td>
<td>157 ± 4</td>
</tr>
<tr>
<td>b (km)</td>
<td>129 ± 3</td>
<td>$143^{+3}_{-6}$</td>
<td>$132^{+6}_{-5}$</td>
<td>139 ± 4</td>
</tr>
<tr>
<td>c (km)</td>
<td>129 ± 3</td>
<td>$96^{+14}_{-4}$</td>
<td>$102^{+10}_{-8}$</td>
<td>86 ± 1</td>
</tr>
<tr>
<td>$R_{\text{equiv}}$ (km)</td>
<td>129 ± 3</td>
<td>126 ± 2</td>
<td>126 ± 2</td>
<td>$123^{+3}_{-1}$</td>
</tr>
<tr>
<td>$\sigma_m$ (km)</td>
<td>11</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$d_{\text{RMS}}$ (km)</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$d_{\text{max}}$ (km)</td>
<td>+15</td>
<td>+11</td>
<td>+12</td>
<td>+9</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>...</td>
<td>$8 \pm 1 \times 10^{18}$</td>
<td>...</td>
<td>$6.1 \pm 0.1 \times 10^{18}$</td>
</tr>
<tr>
<td>$p_b$ (%)</td>
<td>3.1 ± 0.1</td>
<td>3.8 ± 0.1</td>
<td>3.7±0.1</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td>$I/F$ (%)</td>
<td>8.9 ± 0.3</td>
<td>3.4 ± 0.3</td>
<td>4.9±0.3</td>
<td>0.6 ± 0.4</td>
</tr>
</tbody>
</table>

From five occultations (2013-2016)
Chariklo has rings!

- Inner denser ring 2013C1R, ~390 km distance to center.
- Outer tenous ring 2013C2R.
- Gap ~9 km.
- Confirmed in subsequent occultations (2014,...)
- Explains variation of H over time (instead of cometary activity, perspective effects etc.)

Braga-Ribas et al. 2014
Artist’s impression of the Chariklo system
"Only‘ single or double chord Observations.

Try to improve that in 2017…

Leiva et al. 2017

H.- J. Bode
JOA 2017-1
Goals / scientific objectives

- Study the **ring system**: Diane Berard.
- Study the **main body** (physical parameters, shape, etc.): Rodrigo Leiva (2017 campaign).
- „Spin-off“: astrometry, verification of Gaia based predictions etc.
# Occultations 2017: Overview

<table>
<thead>
<tr>
<th>Date &amp; Time</th>
<th>Region</th>
<th>Star Magnitude</th>
<th>Vel. : Max. Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 09 @ 02:25 UT</td>
<td>Southern Africa</td>
<td>14.0 G</td>
<td>4.8 km/s : 52 sec</td>
</tr>
<tr>
<td>June 22 @ 21:18 UT</td>
<td>Southern Africa</td>
<td>14.1 G</td>
<td>22.0 km/s : 11 sec</td>
</tr>
<tr>
<td>July 23 @ 05:44 UT</td>
<td>South America</td>
<td>13.9 G</td>
<td>21.0 km/s : 12 sec</td>
</tr>
</tbody>
</table>

Chariklo: 18.5...18.9 V
What is this?
Of course a telescope
IOTA-ES project “M2”

- 50-cm f/4 portable telescope for occultation expeditions (TNO’s etc.).
- Made (conversion) from a second-hand Skywatcher Alt-Az telescope.
- Weight including wooden transport box ~60 kg.
- Assembled alone* in ~20-30 minutes.
- 2 x Michael
  1 x Konrad ( => M2K ... ?)
Occultation prediction:
star pos. + ephemeris

- Gaia DR1 (~1 Billion stars) released Sept. 2016.
  - New area in (occultation) astronomy!
  - Positional accuracy some mas (<1 mas for 50%), but GDR1 has no PM (except TGAS, but only 2 Mio. stars).
- Most ‘catalog’ orbits (asteroids, TNOs, etc.) by MPC, JPL, etc. have typical ephemeris uncertainties of some ten mas.
- Chariklo’s distance to Earth $\Delta = 15.5$ au (2017.5)
  1 mas in the Sky corresponds to ~11 km.
  => need for “better” orbits.
NIMA: Numerical Integration of the Motion of an Asteroid (Desmars et al.)

- Orbit calculation (differential orbit correction) and short term integration (ephemeris) for occultation predictions.
- Not ‘only’ MPC astrometric observations are used, but also dedicated astrometry made at ESO, Pic du Midi, Calar Alto, Sierra Nevada and Observatorio do Pico dos Dias, and astrometry derived from occultation observations.
- Special weighting scheme during the least squares fitting process, that considers the individual precision of the observation, the number of observations performed during one night by the same observatory, and the presence of systematic errors in the positions.
(10199) Chariklo

Ephemeris solution

- **Observations used**: MPC (1989-2011) + OPD (2011, 2013, 2014) + ESO (2013-2014, GaiaDR1+derivedPM) + Cerro Tololo (2014) + Occ (2013.06.03, GaiaDR1+derivedPM) + Occ (2014.02.16, GaiaDR1+derivedPM) + Occ (2014.03.16, GaiaDR1+derivedPM) + Occ (2014.04.29, GaiaDR1+derivedPM) + Occ (2014.06.28, GaiaDR1+derivedPM) + THA (2015.03, GaiaDR1+derivedPM) + Occ (2014.04.26, GaiaDR1+derivedPM) + ESO (2015.05) + Occ (2015.05.12, GaiaDR1+derivedPM) + SOAR (2015.07) + ESO (2016.04, GaiaDR1+derivedPM) + SHOC (2016.05, Data) + OPD (2016.07) + ESO (2016.06, GaiaDR1+derivedPM) + OPD (2016.07, GaiaDR1+derivedPM) + Occ (2016.07.25, GaiaDR1+derivedPM) + Occ (2016.08.10, GaiaDR1+derivedPM) + Occ (2016.08.15, GaiaDR1+derivedPM) + Occ (2016.10.01, GaiaDR1+derivedPM) + Occ (2017.02.08, GaiaDR1+derivedPM) + Occ (2017.04.09, GaiaDR1+derivedPM) + + OPD (2017.05, GaiaDR1)

- **Observations and residuals file**: occ_rsr.res

- **bsp file**: 10199(Chariklo_nima_v12.bsp

- **Ephemeris file**: ephemeris.res

- **Ephemeris version**: v12

- **Comments**: This is an update version of v11 version with additional observations from OPD (2017.05) and position from OCC (2017.04.09)

- **Date of creation**: 2017-05-31 14:17 (UTC)

<table>
<thead>
<tr>
<th>time</th>
<th>+0</th>
<th>+6</th>
<th>+12</th>
<th>+18</th>
<th>+24</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma (\alpha))</td>
<td>0.012</td>
<td>0.009</td>
<td>0.018</td>
<td>0.014</td>
<td>0.025</td>
</tr>
<tr>
<td>(\sigma (\delta))</td>
<td>0.008</td>
<td>0.009</td>
<td>0.012</td>
<td>0.012</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Time is number of months after last observation (2017-05-03) and \(\sigma\) are in arcsec.
Difference in DE between last version of NIMA and JPL ephemerides. Red dots are occultations positions. Blue dots are CCD observations. Gray area represents the uncertainty of the NIMA ephemeris.
2017 April 09: first prediction: Gaia DR1, but no PM!
Prediction using HSOY (GDR1 + PPMXL) + NIMA v11

More than one path width shift to North compared to ‘plain’ GDR1 (no PM)
Final pre-occultation prediction: GDR1 + PM using UCAC4 as 2nd epoch
Occultation 2017 Apr 9 in Namibia

Post-occultation ground track

=> Prediction GDR1 + PM from UCAC4 + NIMA v11 was very accurate
Occultation 2017 Apr 9 in Namibia
M2 telescope 50 cm f/4 @ ~12 Hz sampling rate

Occultation by Chariklo on 2017 Apr 09, 02:12 UT

Relative Signal

Image number

C1R ingress

main body

C1R egress
# Observations Apr 9 (Namibia)

<table>
<thead>
<tr>
<th>Station</th>
<th>Telescope</th>
<th>Body / Ring(s)</th>
<th>Observer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wabi Lodge</td>
<td>30-cm Meade SCT</td>
<td>Both</td>
<td>Jean-Luc Dauvergne</td>
</tr>
<tr>
<td>Weaver’s Rock Guestfarm</td>
<td>50-cm Alt-Az telescope “M2”</td>
<td>Both</td>
<td>Mike Kretlow</td>
</tr>
<tr>
<td>Outeniqua Guestfarm</td>
<td>40-cm Alt-Az telescope</td>
<td>Clouds</td>
<td>Erick Meza, Martin Scheffel</td>
</tr>
<tr>
<td>Cuno Hoffmeister Memorial Observatory</td>
<td>36-cm Celestron SCT</td>
<td>Clouds</td>
<td>Michael Backes</td>
</tr>
<tr>
<td>ATOM (H.E.S.S. site)</td>
<td>80-cm telescope</td>
<td>Clouds</td>
<td>Felix Jankowsky</td>
</tr>
<tr>
<td>Hakos Astro-Farm (IAS)</td>
<td>50-cm telescope “AK3”</td>
<td>Ring ?</td>
<td>Karl-Ludwig Barth</td>
</tr>
</tbody>
</table>

6 stations, 2 positive observations
The M2 telescope in Namibia
(Weaver's Rock Guestfarm, April 09)
Prediction: 2017 Jun 22

In the table below Gaia presents the three stellar positions to the astronomy community, taken from preliminary Gaia DR2 data, for epoch 2015.5 in the ICRF reference frame.

<table>
<thead>
<tr>
<th>Object to be observed</th>
<th>Description</th>
<th>Chariklo 2015.5 / ICRF</th>
<th>Chariklo 2015.5 / ICRF</th>
<th>Triton 2015.5 / ICRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of occultation event</td>
<td>22 June 2017</td>
<td>23 July 2017</td>
<td>5 October 2017</td>
<td></td>
</tr>
<tr>
<td>Gaia DR2 source ID</td>
<td>67602237558801661440</td>
<td>6737020112089260672</td>
<td>2610107911326516992</td>
<td></td>
</tr>
<tr>
<td>Epoch / Reference frame</td>
<td>2015.5 / ICRF</td>
<td>2015.5 / ICRF</td>
<td>2015.5 / ICRF</td>
<td></td>
</tr>
<tr>
<td>Right Ascension (RA) [degrees]</td>
<td>(\alpha)</td>
<td>283.81521653659905</td>
<td>282.038419778835</td>
<td>343.5768010149869</td>
</tr>
<tr>
<td>RA uncertainty [mas]</td>
<td>(\sigma_{\alpha})</td>
<td>0.052223859934819</td>
<td>0.03963777263392541</td>
<td>0.026564074030629107</td>
</tr>
<tr>
<td>Declination (DEC) [degrees]</td>
<td>(\delta)</td>
<td>-31.522685159905006</td>
<td>-31.442346425165297</td>
<td>-8.002309358044462</td>
</tr>
<tr>
<td>DEC uncertainty [mas]</td>
<td>(\sigma_{\delta})</td>
<td>0.05225161762414635</td>
<td>0.03900893618378824</td>
<td>0.022142168821058843</td>
</tr>
<tr>
<td>Proper Motion in Right Ascension (PM in RA) [mas/yr]</td>
<td>(\mu_{\alpha})</td>
<td>3.2099344713972338</td>
<td>4.026596025279473</td>
<td>27.513673140123508</td>
</tr>
<tr>
<td>Uncertainty of PM in RA [mas/yr]</td>
<td>(\sigma_{\mu_{\alpha}})</td>
<td>0.12086068017989549</td>
<td>0.07293067963207914</td>
<td>0.05352238722669335</td>
</tr>
<tr>
<td>Proper Motion in Declination (PM in DEC) [mas/yr]</td>
<td>(\mu_{\delta})</td>
<td>-2.010735262831512</td>
<td>-6.219325688340016</td>
<td>-1.8210553401369338</td>
</tr>
<tr>
<td>Uncertainty of PM in DEC [mas/yr]</td>
<td>(\sigma_{\mu_{\delta}})</td>
<td>0.10194645902097235</td>
<td>0.0655658281047265</td>
<td>0.045857682351872736</td>
</tr>
<tr>
<td>Parallax [mas]</td>
<td>(\varpi)</td>
<td>0.1572409701013944</td>
<td>0.14967444548457415</td>
<td>1.8956730873515917</td>
</tr>
<tr>
<td>Parallax uncertainty [mas]</td>
<td>(\sigma_{\varpi})</td>
<td>0.06086506896517232</td>
<td>0.04228961058438762</td>
<td>0.028530840302218616</td>
</tr>
</tbody>
</table>

Table: Preliminary data from Gaia DR2 on three stars provided for occultation observations of Chariklo and Triton. (Credit: ESA/Gaia/Dpac, please follow the acknowledgment guidelines as given here and please also cite the Gaia mission paper)
Prediction: GDR2 + NIMA v12
Occultation 2017 Jun 22: Namibia

Post-occultation ground track

Credit: Diane Berard, LESIA, Obs. Paris Meudon
## Observations June 22 (Namibia)

<table>
<thead>
<tr>
<th>Station</th>
<th>Telescope</th>
<th>Body / Ring(s)</th>
<th>Observer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outeniqua Guestfarm</td>
<td>30-cm Meade SCT</td>
<td>Both</td>
<td>Francois Colas, Josselin Desmars</td>
</tr>
<tr>
<td>Onduruquea Guestfarm</td>
<td>50-cm Alt-Az telescope “M2”</td>
<td>Both</td>
<td>Mike Kretlow</td>
</tr>
<tr>
<td>Cuno Hoffmeister Memorial Observatory</td>
<td>40-cm Alt-Az telescope</td>
<td>Both</td>
<td>Erick Meza</td>
</tr>
<tr>
<td>Cuno Hoffmeister Memorial Observatory</td>
<td>36-cm Celestron SCT</td>
<td>Both</td>
<td>Michael Backes, Rhodri Evans</td>
</tr>
<tr>
<td>ATOM (H.E.S.S. site)</td>
<td>80-cm telescope</td>
<td>???</td>
<td>Felix Jankowsky</td>
</tr>
<tr>
<td>Tivoli Astro-Farm</td>
<td>36-cm Meade SCT</td>
<td>Both</td>
<td>Lucie Maquet, Konstantin v. Poschinger</td>
</tr>
<tr>
<td>Hakos Astro-Farm (IAS)</td>
<td>50-cm telescope “AK3”</td>
<td>Ring</td>
<td>Wolfgang Beisker</td>
</tr>
</tbody>
</table>

7 stations, 6 positive observations
Occultation 2017 July 23

Credit: Bruno Sicardy, LESIA, Obs. Paris Meudon
Chariklo July 23, 2017, \((f_c=-10, g_c=-13)\) km

Credit: Bruno Sicardy, LESIA, Obs. Paris Meudon
Chariklo 23 July 2017, HAWK-I DIT= 0.1s (34 images lost/508)

VLT Paranal
HAWK-I K, band

C2R C1R

C1R C2R

Seconds after 05:55:39.52 UT

Credit: Bruno Sicardy, LESIA, Obs. Paris Meudon
Stellar occultation by Chariklo’s rings
July 23, 2017
Danish 1.5m telescope
Lucky Imager, red channel, 30 Hz
Stellar occultation by Chariklo’s rings
July 23, 2017
Danish 1.5m telescope
Lucky Imager, red channel, 30 Hz
Stellar occultation by Chariklo’s rings
July 23, 2017
Danish 1.5m telescope
Lucky Imager, red channel, 30 Hz
M2 telescope 50 cm f/4 @ ~12 Hz sampling rate

Occultation by Chariklo on 2017 Apr 09, 02:12 UT

- C1R ingress
- Main body
- C1R egress
Tolar Grande, Argentina, 148 habitants (?)
Summary of 2017 campaign

<table>
<thead>
<tr>
<th>Date</th>
<th># stations</th>
<th># chords</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 9</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>June 22</td>
<td>7 (6)</td>
<td>6 (7)</td>
</tr>
<tr>
<td>July 23</td>
<td>&gt;= 15</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>&gt;= 28</td>
<td>21 (8: 2013-2016)</td>
</tr>
</tbody>
</table>
Conclusion

- 2017 campaign was a big success. All three scheduled events were observed. July 23 is the best ever observed occultation by Chariklo, at least in terms of coverage, etc.

- A lot of new data to study the ring system and to (re-)constrain the physical parameters (shape etc.) of the main body.

- Even with GDR1 positions (epoch 2015.0) the knowledge of PMs for TNO occultation is important. GDR2!

- NIMA ephemeris for specific objects like Chariklo is very accurate (< 100 km on FP).
Still enough room for more science / open questions

- Origin and evolution of the ring system.
- (Shepard) moons ?
- Ring arcs ?
- Improve constrains of physical parameters (dimension, shape (rings !), mass & bulk density).
- ...

Acknowledgment

- Lucky Star Team at LESIA, Paris Meudon Observatory: Bruno Sicardy, Diane Berard, Josselin Desmars, Erick Meza, Rodrigo Leiva, ...
- Financial support by the Lucky Star ERC project
- All the expedition participants
- Local observers and helpers
- IOTA-ES
- ...

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Thank You for Your attention!