

Prediction of stellar occultations by distant solar system bodies in the Gaia era

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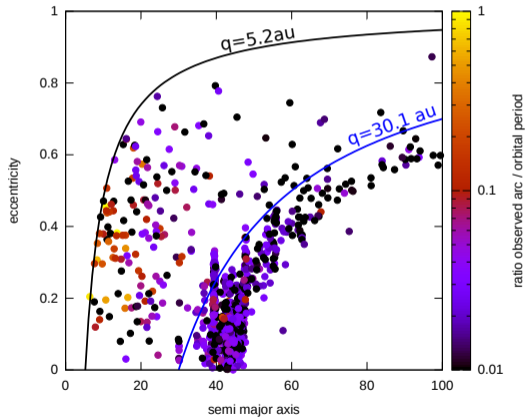
Symposium IAU 330
Astrometry and Astrophysics in the Gaia sky



TNOs and Centaurs

TNO & Centaurs in solar system

- ▶ **Trans Neptunian Objects** are objects beyond Neptune and **Centaurs** are objects between Jupiter and Neptune
- ▶ Scientific interests: unaltered witnesses of the solar system formation
- ▶ Faint and poorly known objects (physical characteristics, **orbits**)



Stellar occultations

Stellar occultations

- ▶ **Stellar occultation** of a star by a TNO
- ▶ Measure of the time and flux of the star during occultation

Physical parameters measurable by stellar occultations

- ▶ Size/shape
 - ▶ Binarity/Multiplicity
 - ▶ Atmosphere (composition, density)
 - ▶ Rings system
-
- ▶ Currently the only way to access these parameters accurately from ground-based observations (see B.Sicardy and D.Bérard talks)

Prediction of stellar occultations

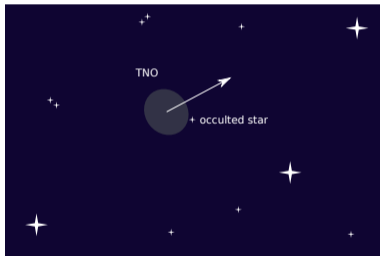
Prediction of stellar occultations

Prediction requires both accurate position of

- ▶ **star** ▶ **Astrometry**
- ▶ **object** ▶ **Ephemeris**

Difficult challenge

- ▶ Distant objects 15-90 au and small
100-2000km
- ▶ Apparent diameter of TNO is about 10-50
mas
- ▶ 30mas is 1€ seen at 200km



Uncertainties in the predictions

Sources of uncertainty in the **star's position**

- ▶ Systematic errors in stellar catalogues ▶ Not a problem anymore with Gaia-DR1
- ▶ Uncertainty of proper motion

Sources of uncertainty in **ephemeris**

Uncertainty in ephemeris is mainly due to astrometric systematic errors

- ▶ Bad observations
- ▶ Zonal errors in stellar catalogues
- ▶ Other systematic errors (telescope, reduction, ...)

Methods of Predictions

History of methods

- ▶ 2009-2013 : Offset Method (*Assafin et al.*, 2011; *Camargo et al.*, 2014)
- ▶ 2013-...: NIMA Method (*Desmars et al.*, 2015)

Advantages of the NIMA method

- ▶ We determine our own ephemeris (NIMA)
- ▶ We can use **more astrometric observations** for orbit determination : MPC + Offset (obs by Rio team) + unpublished + past positive occultations
- ▶ Observations treatment (bias correction), control of weighting process (V_{obs})

Astrometry of previous occultations

Previous occultations

- ▶ 45 predicted occultations for 18 TNOs have been successfully detected in the last few years 2009-2017 (Eris, Makemake, Chariklo,...)

Astrometry of occultations

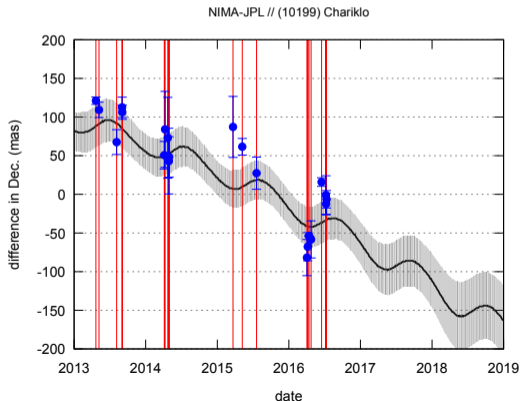
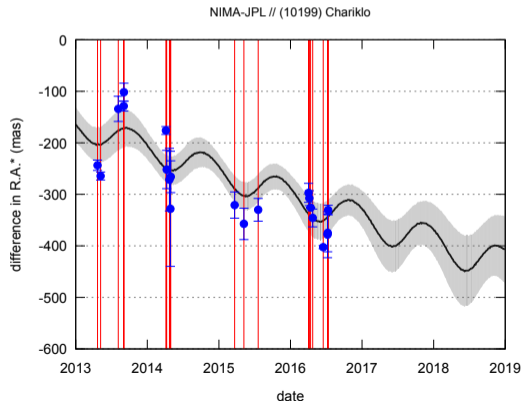
- ▶ Accurate astrometric position can be determined from occultations
 - ▶ The uncertainty of the position is only due to uncertainty in occulted star position
 - ▶ With Gaia-DR1, uncertainty in the star position is mainly dominated by the uncertainty in the proper motion
 - ▶ $\sim 5 - 20$ mas with Gaia-DR1
 - ▶ $50 - 70$ mas for previous catalogues (ex: UCAC4)
 - ▶ expected < 1 mas with Gaia-DR2
- ▶ Feed the ephemeris with the astrometric position of occultations

Chariklo's ephemeris Before Gaia



Observations

- ▶ MPC (1988-2011) + Offset obs (OPD, ESO, ...) reduced with UCAC4

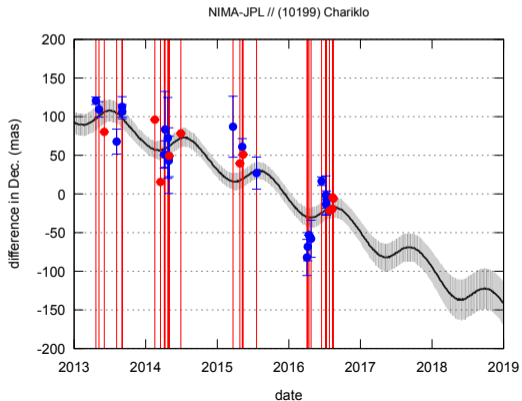
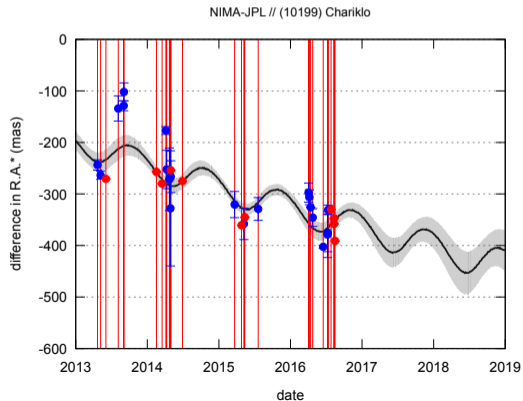


Chariklo's ephemeris Before Gaia



Observations

- ▶ MPC (1988-2011) + Offset obs (OPD, ESO, ...) reduced with UCAC4 + 11 occultations (2013-2016) with UCAC4 stars

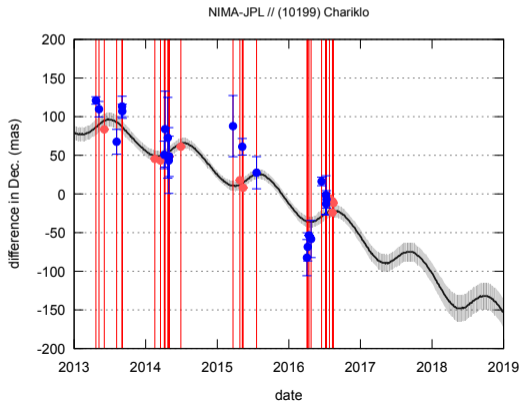
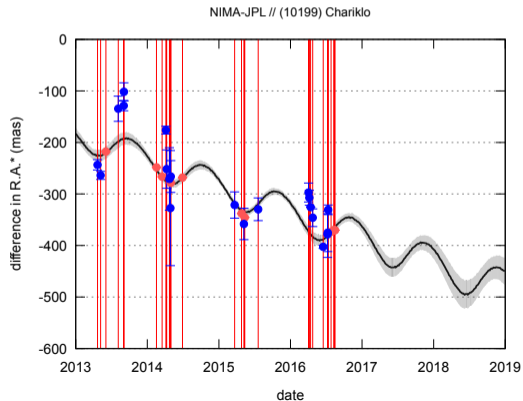


Chariklo's ephemeris After Gaia



Observations

- ▶ MPC (1988-2011) + Offset obs (OPD, ESO, ...) reduced with UCAC4 + 11 occultations (2013-2016) with Gaia-DR1 stars

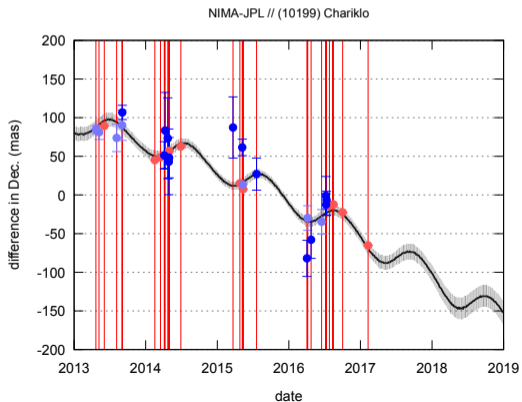
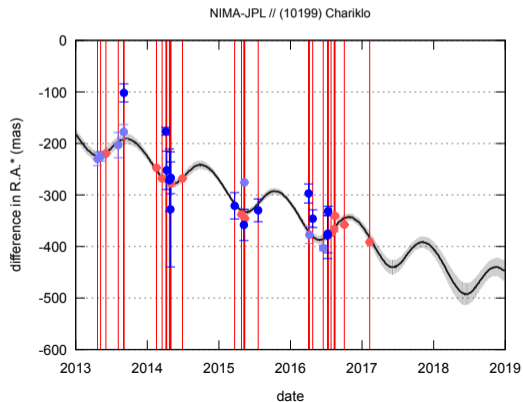


Chariklo's ephemeris After Gaia



Observations

- ▶ MPC (1988-2011) + Offset obs (OPD, ESO, ...) partially reduced with Gaia-DR1 + 13 occultations (2013-2017) with Gaia-DR1 stars ▶ latest NIMA version (v11)

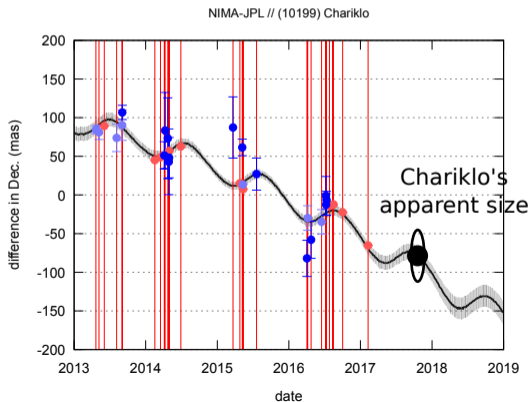
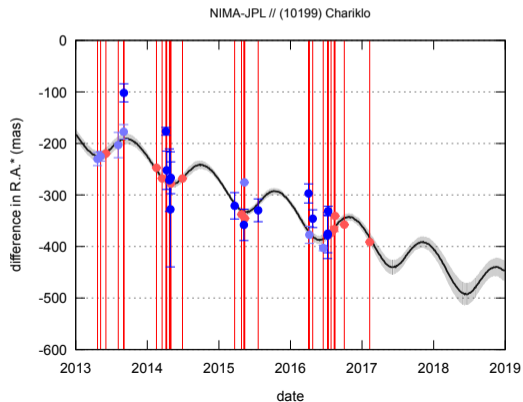


Chariklo's ephemeris After Gaia



Observations

- ▶ MPC (1988-2011) + Offset obs (OPD, ESO, ...) partially reduced with Gaia-DR1 + 13 occultations (2013-2017) with Gaia-DR1 stars ▶ latest NIMA version (v11)



Proper motion

Sources of proper motion

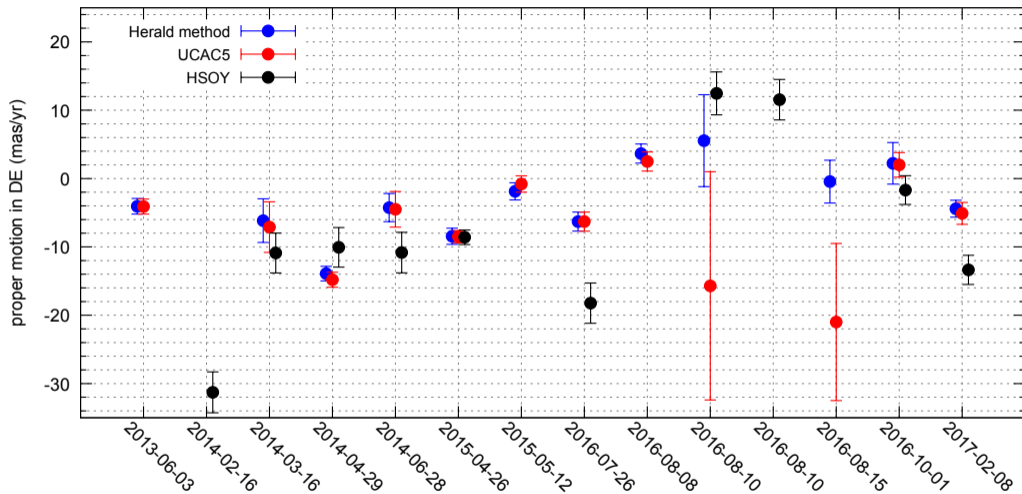
- ▶ TGAS (only for "bright" stars) ▶ mean magnitude of occulted stars $\sim 13 - 14$
- ▶ UCAC5 ([Zacharias et al., 2017](#))
- ▶ Hot Stuff for One Year (HSOY) ([Altmann et al., 2017](#))
- ▶ GAIA-PS1-SDSS (GPS1) proper motion catalog ([Tian et al., 2017](#))
- ▶ Dave Herald's method

Herald's method

- ▶ Derive from UCAC4 positions and proper motion, the UCAC4 position at UCAC4 epoch $E_U: (\alpha_U, \delta_U)$
- ▶ Gaia position at Gaia epoch $E_G: (\alpha_G, \delta_G)$
- ▶ Proper motion:

$$\mu_\alpha = \frac{\alpha_U - \alpha_G}{E_U - E_G}; \mu_\delta = \frac{\delta_U - \delta_G}{E_U - E_G}$$

Proper motion



Comparison of proper motion in DEC. for the stars involved in Chariklo's occultations

Occultation by Chariklo - 9 April 2017

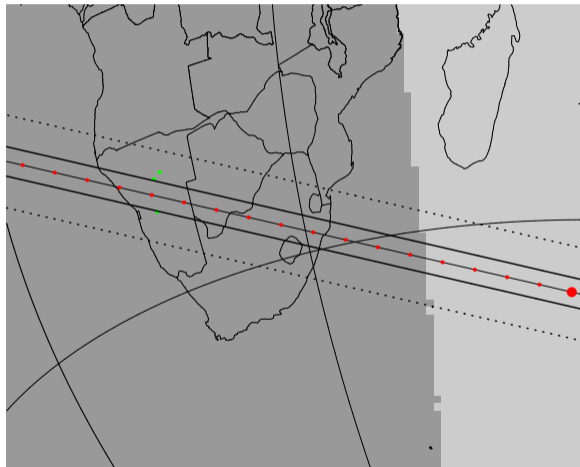
Chariklo: GaiaDR1, NIMAv10 ephem.

Offset (mas): 0.0 0.0

3 positive chords observed in Namibia : 2 by body+rings (1 almost central), 1 by rings

Prediction

- ▶ NIMAv10
- ▶ Gaia-DR1



d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	G*	J*	long
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09	04	2017	02 25 10.	19 04	03.6287	-31 17 15.224	0.044	192.99	4.78	15.47	12.4	9.6	52.
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Occultation by Chariklo - 9 April 2017

Chariklo: GaiaDR1+pmUCAC5, NIMAv10 ephem.

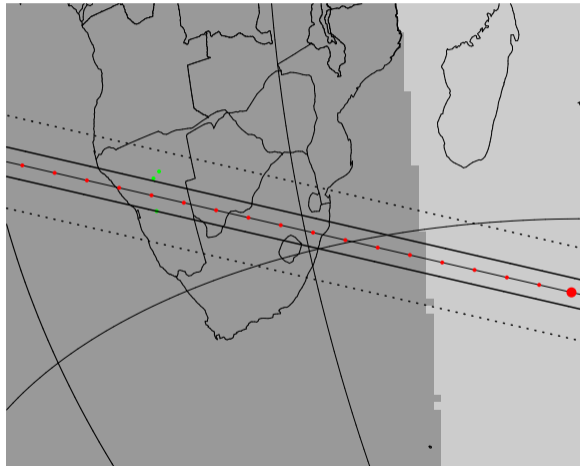
Offset (mas): 0.0 0.0

Prediction

- ▶ NIMAv10
- ▶ Gaia-DR1 + proper motion UCAC5

$$\mu_{\alpha} = -3.00 \pm 3.60 \text{ mas/yr}$$

$$\mu_{\delta} = 1.00 \pm 3.70 \text{ mas/yr}$$



d	m	year	h:m:s UT	ra__dec__J2000_candidate	C/A	P/A	vel	Delta	G*	J*	long
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09	04	2017	02 24 54.	19 04 03.6282 -31 17 15.222	0.045	192.99	4.78	15.47	12.4	9.6	52.
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Occultation by Chariklo - 9 April 2017

Chariklo: GaiaDR1+pmDHerald, NIMAv10 ephem.

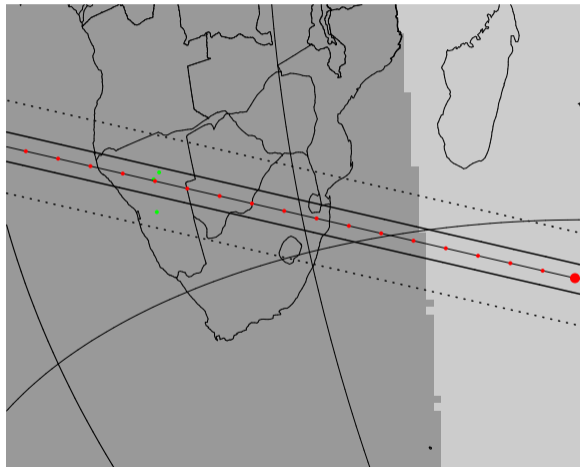
Offset (mas): 0.0 0.0

Prediction

- ▶ NIMAv10
- ▶ Gaia-DR1 + proper motion (Herald's method)

$$\mu_{\alpha} = -3.74 \pm 1.52 \text{ mas/yr}$$

$$\mu_{\delta} = -4.61 \pm 3.23 \text{ mas/yr}$$



d	m	year	h:m:s UT	ra	dec	J2000_candidate	C/A	P/A	vel	Delta	G*	J*	long
09	04	2017	02 24 57.	19 04	03.6281	-31 17 15.234	0.033	192.99	4.78	15.47	12.4	9.6	52.

Conclusion and Perspectives

Conclusion

- ▶ Gaia-DR1 greatly improves the predictions of occultations (Pre-Gaia: 30-40mas, DR1: ~ 10 mas, DR2: < 1 mas)
- ▶ Accurate astrometric positions from positive occultations help to refine orbits without direct observations of the body with Gaia
- ▶ A precision of few mas is reachable now for some objects (Chariklo, Pluto) leading to grazing occultations/central flash (see talk by D.Bérard)
- ▶ Still an issue with the proper motion

Perspectives

- ▶ **Next important step : Gaia-DR2** (for both astrometry of TNOs and stars position)
- ▶ Improve the ephemeris (by new reduction of observations with Gaia DR2) + direct observations of some TNOs/Centaurs with Gaia (mag < 20)
- ▶ Astrometry on surveys (LSST, ...) ▶ see poster B.3. (J.Camargo)



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 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.

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

Date Filter: 2017-03-31 2017-08-01

Object Selection: Choose an object

Magnitude Filter: 5.0 16.0

Date	Object	G Magnitude	Map
2017-Mar-31 11:55	Ixion	15.4	
2017-Mar-31 16:27	2003AZ84	15.5	
2017-Apr-01 20:37	2002MS4	15.6	

Predictions for 2017

- ▶ For scientific purposes, we specifically study 55 TNOs/Centaurs
- ▶ Predictions of occultation with NIMA ephemeris and Gaia-DR1

This work is funded by the ERC Lucky Star



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