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

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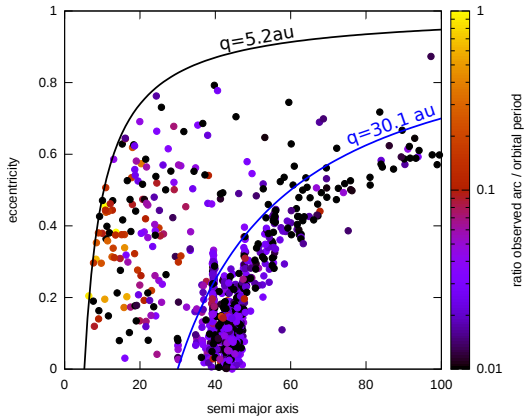
Symposium IAU 330
Astrometry and Astrophysics in the Gaia sky

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

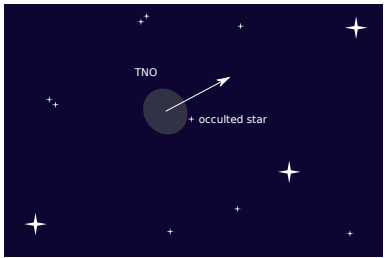
- Currently the only way to access these parameters accurately from ground-based observations (see B.Sicardy and D.Bérard talks)

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 used **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

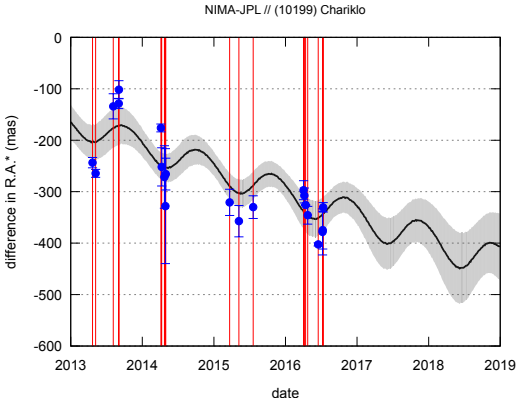
- Accurate astrometric position can be determined from occultations
- The uncertainty of the position is only due to uncertainty in occulted star position
- With Gaia-DR1, uncertainty in the star position is mainly dominated by the uncertainty in the proper motion
  - $\sim 5 - 20$mas with Gaia-DR1
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

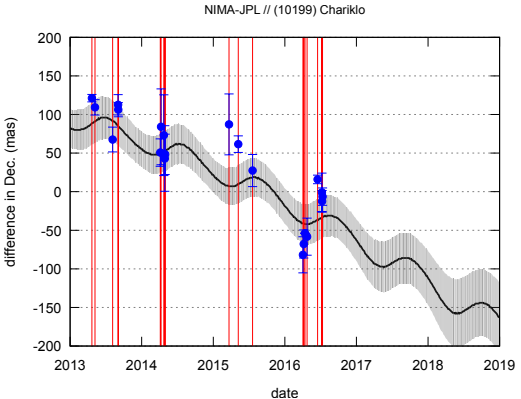
▶ Feed the ephemeris with the astrometric position of occultations

Chariklo's ephemeris Before Gaia

Observations

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

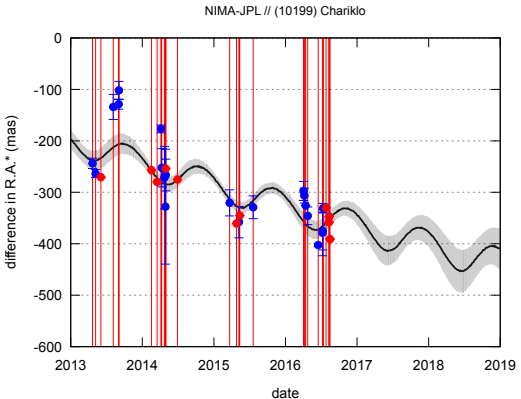


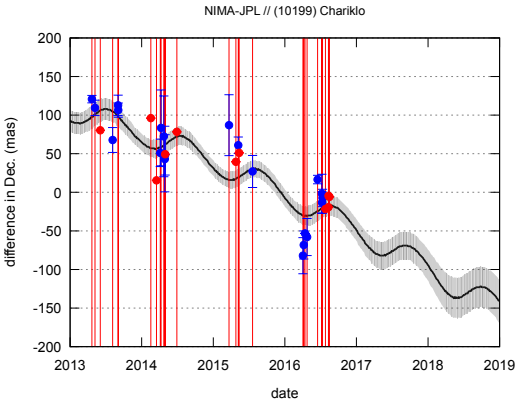


Chariklo's ephemeris Before Gaia

Observations

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

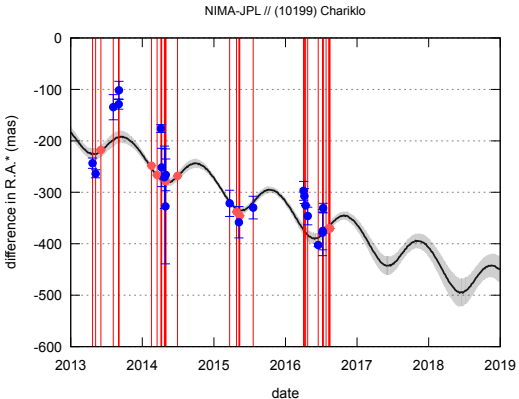


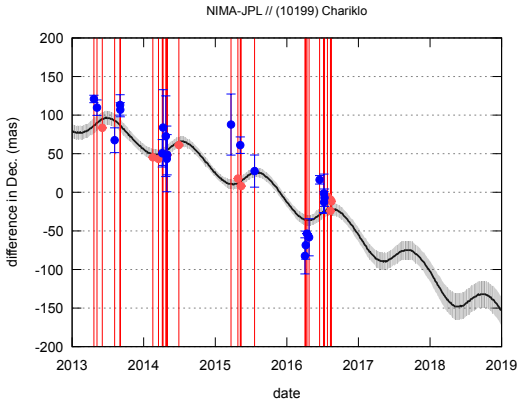


Chariklo's ephemeris
After Gaia

Observations

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

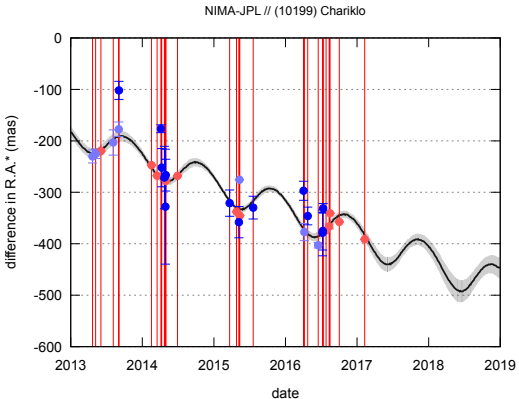


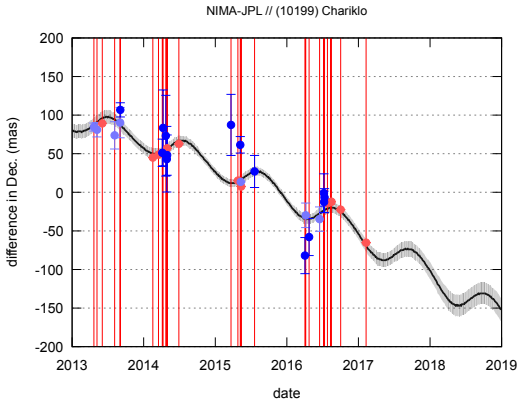


Chariklo's ephemeris
After Gaia

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
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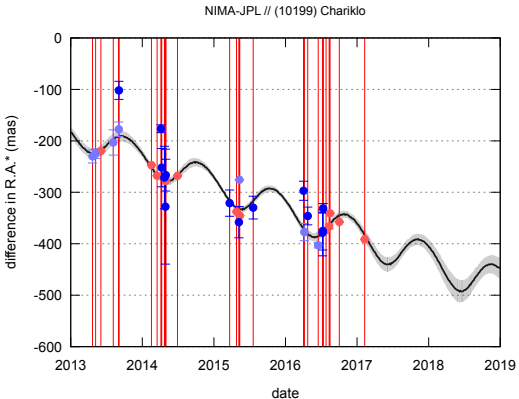
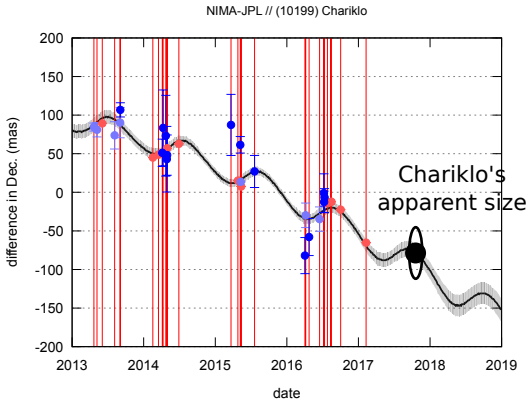




Proper motion

Sources of proper motion

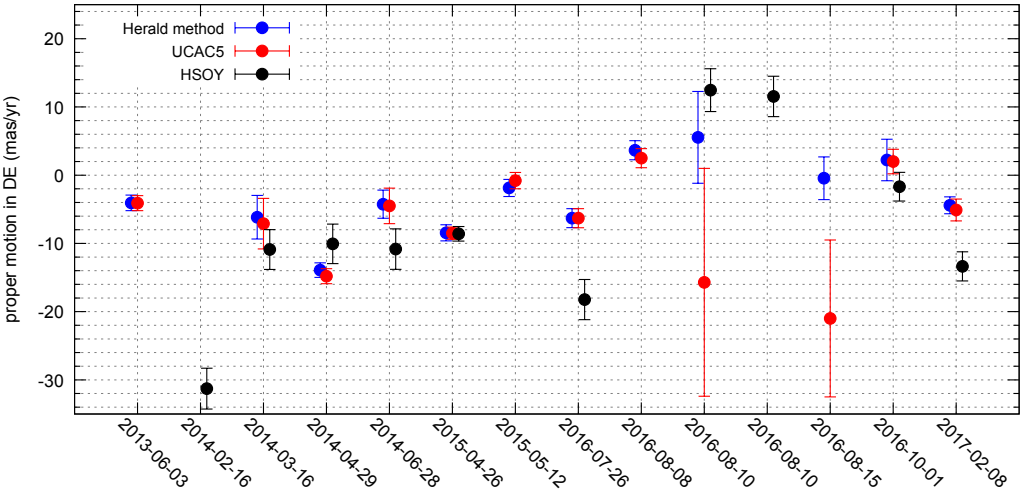
- TGAS (only for "bright" stars) ▶ mean magnitude of occulted stars $\sim 13 - 14$
- UCAC5 (Zacharias *et al.*, 2017)
- Hot Stuff for One Year (HSOY) (Altmann *et al.*, 2017)
- GAIA-PS1-SDSS (GPS1) proper motion catalog (Tian *et al.*, 2017)
- Dave Herald's method

Herald's method

- Derive from UCAC4 positions and proper motion, the UCAC4 position at UCAC4 epoch E_U: (α_U, δ_U)
- Gaia position at Gaia epoch E_G : (α_G, δ_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



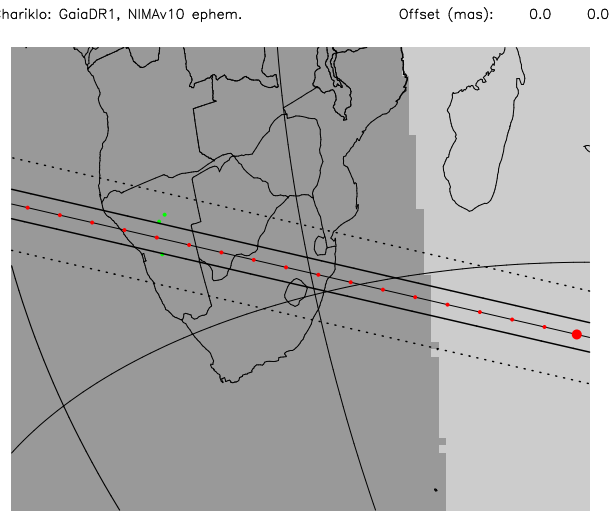
Comparison of proper motion in DEC. for the stars involved in Chariklo's occultations

Occultation by Chariklo - 9 April 2017

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

Prediction

- NIMAv10
- Gaia-DR1



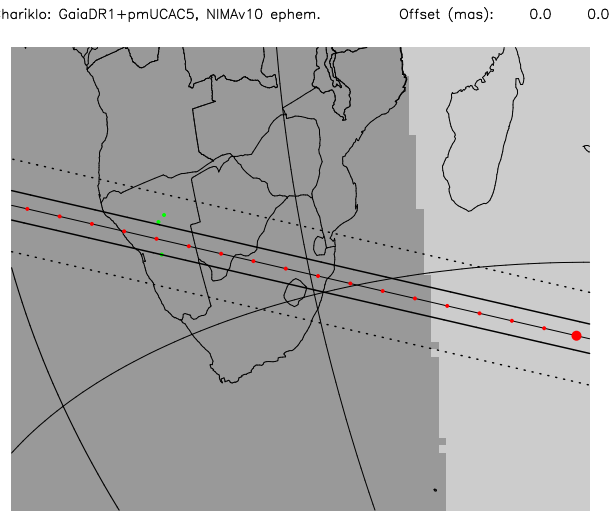
d	m	year	h:m:s UT	ra___dec___J2000_candidate	C/A	P/A	vel	Delta	G*	J*	long
09	04	2017	02 25 10.	19 04 03.6287 −31 17 15.224	0.044	192.99	4.78	15.47	12.4	9.6	52.

Occultation by Chariklo - 9 April 2017

Prediction

- NIMAv10
- Gaia-DR1 + proper motion UCAC5

$$\mu_\alpha = -3.00 \pm 3.60 \text{ mas/yr}$$
$$\mu_\delta = 1.00 \pm 3.70 \text{ mas/yr}$$

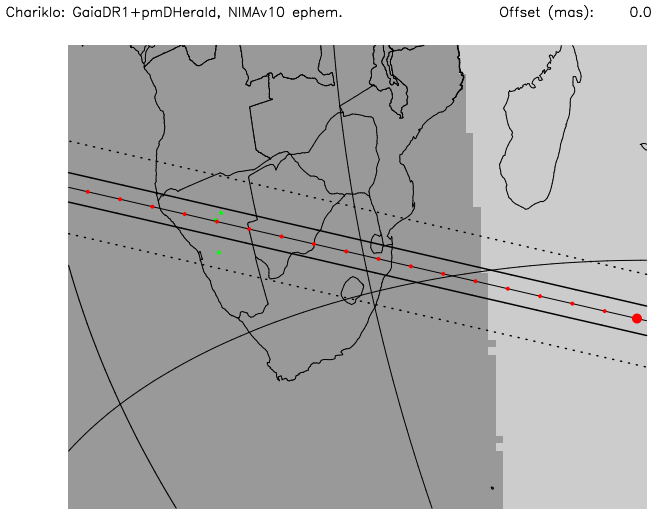


Occultation by Chariklo - 9 April 2017

Prediction

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

$$\mu_\alpha = -3.74 \pm 1.52 \text{ mas/yr}$$
$$\mu_\delta = -4.61 \pm 3.23 \text{ mas/yr}$$



Conclusion and Perspectives

Conclusion

- Gaia-DR1 greatly improves the predictions of occultations (Pre-Gaia: 30-40mas, DR1: $\sim$ 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

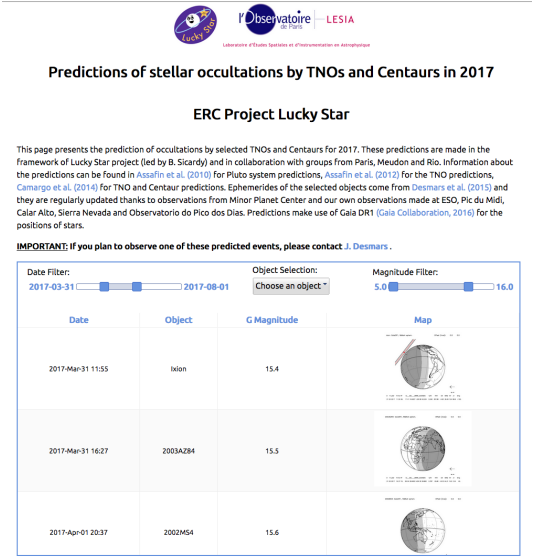
Perspectives

- **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 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/