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Exploring the Solar System using stellar occultations

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Abstract. Stellar occultations by solar system objects allow kilometric accuracy, permit the detection of tenuous atmospheres (at nbar level), and the discovery of rings. The main limitation was the prediction accuracy, typically 40 mas, corresponding to about 1,000 km projected at the body. This lead to large time dedicated to astrometry, tedious logistical issues, and more often than not, mere miss of the event. The Gaia catalog, with sub-mas accuracy, hugely improves both the star positions, resulting in achievable accuracies of about 1 mas for the shadow track on Earth. This permits much more carefully planned campaigns, with success rate approaching 100%, weather permitting. Scientific perspectives are presented, e.g. central flashes caused by Plutos atmosphere revealing hazes and winds near its surface, grazing occultations showing topographic features, occultations by Chariklos rings unveiling dynamical features such as proper mode "breathing".

Keywords. occultations, astrometry, solar system: general, planets: rings, Kuiper Belt

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1. Introduction

Stellar occultations represent a very poweful tool that allow us to study a great variety of planetary bodies in the solar system. They occur when these bodies pass in front of a star. The photometric monitoring of those events at a given site permit to measure the length of the occultation phenomenon, thus providing one "occultation chord" per site. Combining those chords, one may obtain the shape and size of the object at kilometric accuracy. In fact, that accuracy is linked to the acquisition rate during the event. As the typical speed of the occultation shadow on Earth's surface is 20 km s^{-1}, an acquisition rate of, say, ten frames per second (fps) results in a resolution of 2 km per data point on the object. Moreover, the occultation may be not sudden, but gradual, due to the presence of a tenuous atmosphere. The sensitivity of ground-based occultations is such that pressure levels as small as a few nbar can detected. Finally, material surrounding the body, like rings, cometary jets or dust shells, can be revealed, while remaining out of reach of any direct imaging techniques.

Ultimately, the resolution obtained during an occultation is set by the Fresnel diffraction, which has a scale of $\lambda_F = \sqrt{\lambda D/2}$, where λ is the wavelength of observation and D is the geocentric distance of the object. For events involving remote objects in the solar systems like Trans-Neptunian Objects (TNOs), with $D = 20 - 50$ au, this results in $\lambda_F <\sim 1$ km. Moreover, depending on the type and magnitude of the star, the stellar diameter is also of the order of a fraction of km to a few km when projected at the object. This resolution power is far larger, by almost 3 orders of magnitude, than any classical direct imaging: for instance it is at best 500 km using the Hubble Space Telescope to observe Pluto.

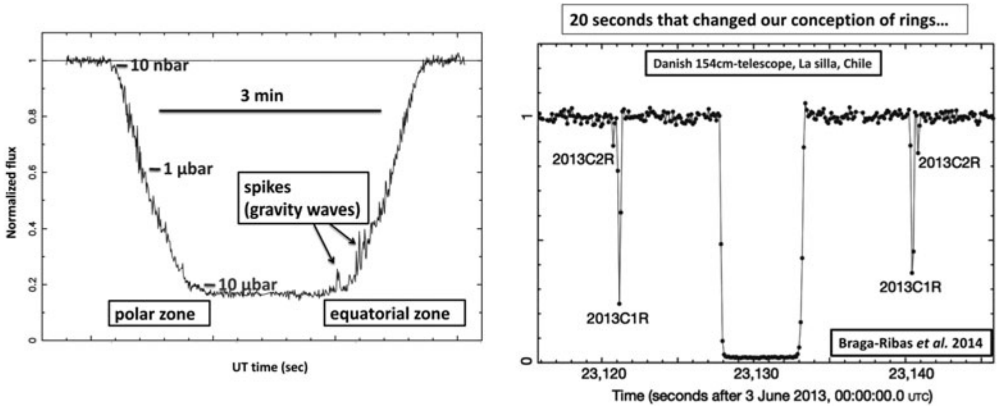

Figure 1. Left - An occultation by Pluto's atmosphere observed on July 18, 2012 with the adaptive optics camera NACO attached to the Very Large Telescope of the European Southern Observatory. The black horizontal bar indicates the time scale (3 minutes) and the red labelling-shows the typical atmospheric levels reached along the occultation light curve(obtained here at a rate of 5 fps). Right - One of the discovery light curves of Chariklos rings, obtained on June 3, 2013 from the Danish telescope at La Silla (Chile). The light curve was obtained at a rate of 10 fps and shows the occultation by the main body at the center, with the symmetrical detections of two rings (C1R and C2R) that surround that small object with diameter of about 250 km.

2. Results obtained by stellar occultations

Stellar ocultations have an impressive record of discoveries, published in high impact journals as *Nature* or *Science*. For instance, they allow to discover Uranus' narrow and dense rings (Bhattacharyya & Bappu 1977, Elliot *et al.* 1977), Neptune's ring arcs (Hubbard *et al.* 1986, Sicardy *et al.* 1986), measure Neptune's shape (Sicardy *et al.* 1986), probe Titan's atmosphere (Sicardy *et al.* 1990) and Triton's atmosphere (Elliot *et al.* 1997), discover material around the Centaur object Chiron (Elliot *et al.* 1995), reveal a spectacular expansion of Pluto's atmosphere between 1988 and 2002 (Elliot *et al.* 2003, Sicardy *et al.* 2003), measure the size of its satellite Charon at kilometric accuracy (Gulbis *et al.* 2006, Sicardy *et al.* 2006a), as well as the sizes of the very remote dwarf planets Eris (Sicardy *et al.* 2011) and Makemake (Ortiz *et al.* 2012), and more recently, discover dense and narrow rings around the Centaur object Chariklo, the first body ever known to possess ring besides the giant planets (Braga-Ribas *et al.* 2014).

Fig. 1 shows two examples of results obtained using stellar occultations, one illustrating the probing of Pluto's atmosphere, and the other one showing the discovery of rings around Chariklo.

3. The Gaia era

The main limitation of occultation have been so far the prediction accuracy. In fact, the typical errors induced by the pre-Gaia catalog were typically 20-40 milliarcsec (mas), depending on the star and the catalog used. This corresponds to typically 500-900 km at Pluto. As the latter has a radius of 1,190 km, this means that more than often, the event was missed just because of star catalog errors, not talking of course about smaller bodies for which that problem worsens.

This is illustrated in Fig. 2, where we compare a pre-Gaia prediction with a prediction using the Gaia Data Release 1 (DR1), combined with an improved Pluto's ephemeris generated by the Jet Propulsion Laboratory (JPL) before the flyby of the dwarf planet by the NASA spacecraft *New Horizons*. Note the drastic improvement brought by the

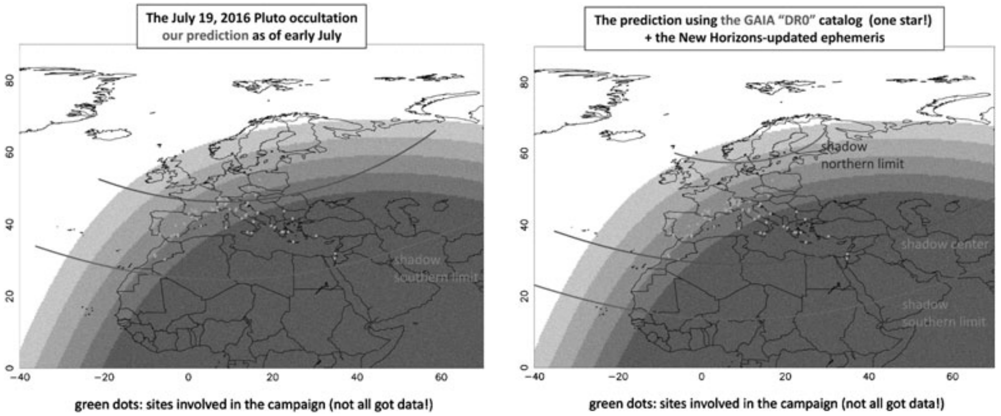

Figure 2. Left - Predicted of Pluto's shadow track on Earth (July 19, 2016 occultation) based on pre-Gaia astrometric catalogs. The lower curved line is the southern limit of the atmospheric shadow, while the middle curved line is the centrality of the event, where a central flash was planned. The dots indicate the locations of the sites involved in the campaign (some of them eventuelly clouded out). The darkest zone corresponds to astronomical night (Sun 18 deg below local horizon), while the white part of the map corresponds to daylight. Right - The same using the GAIA DR1 star position, showing a large drift to the south. The actual event was very close to that prediction, with an offset of about 5 mas with respect to the prediction (correspnding to less tha 100 km for the shadow track on Earth).

Gaia DR1 release. In this particular example, there was of a large error on the star position, which reached 100 mas, probably due to a local catalog problem in the region of the sky where the star was found.

The Gaia catalogs are free of such local problems, and permit accurate predictions well in advance. This is illustrated in Fig. 3, where we compare the pre-Gaia types of predictions with the post-DR1 predictions. The improvement is impressive, with a factor almost four in angular accuracy (typically 10 mas, vs. some 40 mas previously).

Note that because the DR1 catalog lacks of the star proper motions, its accuracy is degraded by several mas per year as the star moves with respect to its DR1 (2015.0) position. Morover, some stars had not enough visits in the DR1 catalog, resulting in cumulated errors of as much as 20 mas for their positions as of 2017.

4. The forthcoming Gaia releases and their implications

The main improvement brought by DR2 will be the access to the star proper motion, with an eventual accuracy on the star position of a fraction of mas. As an example, this corresponds to a few kilometers at the level of Chariklo and its rings, and typically 10 km for the most remote TNOs. This is a tremendous leap forward, and will represent a new era in the domain of stellar occultations by solar system objects. At this stage, the main limitation will be the internal accuracy of the body ephemeris. The ephemeris will be improved either by the bootstrapping approach illustrated in Fig. 3, or by looking at close angular approches (appulses) between the object and Gaia DR2 star positions. In a few cases, Gaia itself will release positions of bodies that can be used for ephemeris improvement.

This said, among the future applications of DR2, we may quote a few illustrative examples:

- **Topographic features** at the surface of small bodies may reach 10 km in height or depth. Thus, carefully planned occultations will permit to organize grazing events,

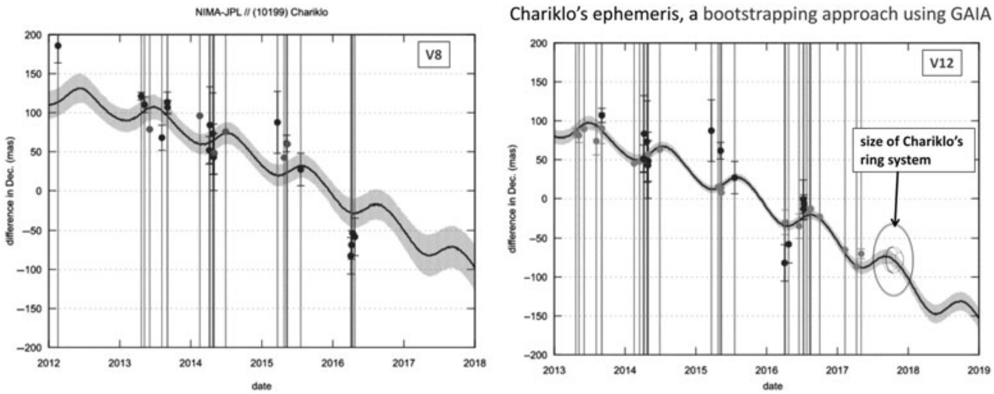

Figure 3. An illustration of the improvements of occultation predictions provided by Gaia. Left - The difference in declination between the NIMA v8 Chariklo's ephemeris and a reference ephemeris from the JPL plotted vs. time (taken from http://josselin.desmars.free.fr/tno/, see also Desmars *et al.* 2015). It was obtained using classical astrometric measurements (blue points) and previous positive stellar occultations (red points). The gray zone is the uncertainty associated with the ephemeris. Right - The same using positive Chariklo stellar occultations between June 2013 and April 2017, and star positions from the DR1 Gaia catalog (Gaia Collaboration 2016a, Gaia Collaboration 2016a). Note the drastic improvement of Chariklo's ephemeris quality, which is now sufficiently accurate to plan occultations by the rings and the main body This is illustrated by the insert of Chariklo's system in the right panel.

where various stations separated by a few kilometers will detect the star "flickering" along the limb, thus measuring these features, as was done in the 1970's to map the Moon topography near its poles. In other words, we will be in the position of not only monitor the occultations, but also use them for "geological" purposes. A particularly interesting object is Chariklo, as km-sized features and a possible elongation of the body may give rise to important mean motion resonances with the rings. Also, an initial debris disk surrounding that Centaur (and from which the rings emerged) may have left an equatorial ridge that could be detected during grazing occultations.

- Concerning objects with **atmosphere** (e.g. Titan, Triton or Pluto), there is a small region near the shadow center where a "central flash" can be observed. It stems from the focusing of light toward the observer, due to the refraction by the deepest atmospheric layers reached during the occultation. Such flashes provide accurate information on the distortions of the atmosphere, and therefore, the zonal wind regimes that maintain those distortions. Moreover, by observing at various wavelengths, we may detect a differential extinction that constrains the particle size distribution of the hazes responsible the dimming of stellar rays (see e.g. Sicardy *et al.* 2006b)
- **Chariklo's rings** may be not perfectly circular, as normal modes can distort their orbits, as observed for the Uranian rings (French *et al.* 1991). Again, the Gaia releases, together with updated Chariklo's ephemeris, will allow a good coverage in longitude of the rings, and then a possible detection of proper modes with various azimuthal numbers. This in turn will permit to estimate Chariklo's mass, its dynamical oblateness J_2 and the ring surface densities.
- Needless to say, the greatly enhanced accuracy of occultation predictions will allow us to observe many more events, thus **triggering the findings of still unknown remarkable features**. Among those potential discoveries, we may quote new ring systems, atmospheres around dwarf planets, contact binaries, cometary material, and seasonal effects in Titan, Pluto or Triton's atmosphere as time passes by.

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References

Braga-Ribas, F. *et al.* 2014, *Nature*, 508, 72

Bhattacharyya, J. C. & Bappu M. K. V. 1977, *Nature*, 270, 503

Elliot, J. L. *et al.* 2015, *Astron. & Astroph.*, 584, A96

Elliot, J. L. *et al.* 1977, *Nature*, 267, 328

Elliot, J. L. *et al.* 1995, *Nature*, 373, 46

Elliot, J. L. *et al.* 1997, *Science*, 278, 436

Elliot, J. L. *et al.* 2003, *Nature*, 424, 165

French, R. G. *et al.* 1991, in: J.T. Bergstralh, E.D. Miner & M.S. Matthews (eds.) *Uranus* (Univ. of Arizona Press, Tucson), p. 327

Gaia Collaboration, Brown, A. G. A., Prusti, T. *et al.* 2016a, *Astron. & Astroph.*, 595, A1

Gaia Collaboration, Lindegren, L., Lammers, U. *et al.* 2016a, *Astron. & Astroph.*, 595, A2

Hubbard, W. B. *et al.* 1988, *Nature*, 336, 462

Gulbis, A. A. *et al.* 2006, *Nature*, 439, 48

Hubbard, W. B. *et al.* 1986, *Nature*, 319, 636

Lellouch, E. *et al.* 1986, *Nature*, 324, 227

Ortiz, B. *et al.* 2012, *Nature*, 320, 729

Sicardy, B. *et al.* 1986, *Nature*, 320, 729

Sicardy, B. *et al.* 1990, *Nature*, 343, 350

Sicardy, B. *et al.* 2003, *Nature*, 424, 168

Sicardy, B. *et al.* 2006a, *Nature*, 439, 52

Sicardy, B. *et al.* 2006b, *J. Geophys. Res.*, 111, E11S91

Sicardy, B. *et al.* 2011, *Nature*, 478, 493