

# Exploration of the Outer Solar System by Stellar Occultations

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Received: 20 February 2009 / Accepted: 10 June 2009 / Published online: 27 June 2009  
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**Abstract** Stellar occultations are a powerful method for exploring the outer solar system, where faintness and small angular diameters prevent us from exploring in details objects like satellites, rings, or Kuiper Belt Objects. Unique kilometric spatial resolutions or better can be reached through that method. Occultations usually observe identified objects whose trajectory is known, though the occultation events might be difficult to predict. It is also possible to explore populations of small objects populations whose density in the sky plane is large enough to search for serendipitous occultations. Various instrumental methods exist for both predicted and serendipitous occultation, both needing fast photometric recordings of target stars.

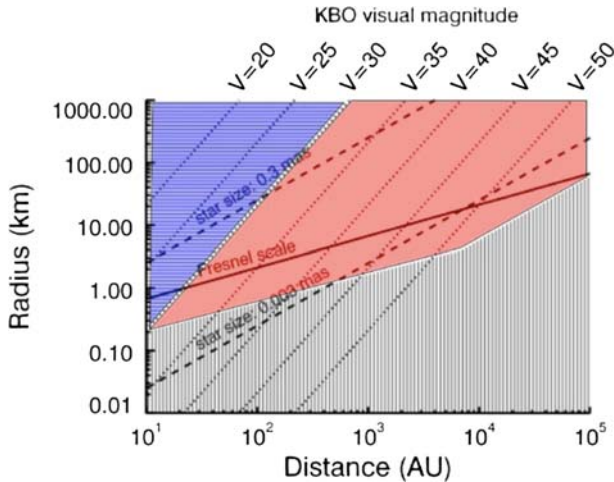
**Keywords** Kuiper belt · Stellar occultations · Observations

## 1 Introduction

Our knowledge on the outer solar system has dramatically evolved in recent years, after the discovery of hundreds of objects in the Kuiper Belt. These Kuiper belt Objects (KBOs) are thought to be the remnants of the outermost population of bodies formed during the early solar system stage. Later perturbations by the giant planets have sculpted this population into various dynamical populations (Morbidelli et al. 2008). These discoveries have in particular resulted into an improved scenario for planetary formation, suggesting significant migrations of the outer planets, with Pluto's status evolving from planet to KBO. With diameters of 2,500 km or so at most, those objects subtend angles smaller than 0.1 arcsec on the sky, and usually much less. Also, many of those objects are very faint (for instance, a 10 km KBO at a distance of 43 AU would typically have a magnitude R 30), rendering classical imaging inefficient, while stellar occultations can provide kilometric resolution or better (Fig. 1).

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**Fig. 1** The objects detectable by direct observations (*blue zone*) and by occultations (*pink zone*, with a 4 m telescope and an integration frequency of 40 Hz)

In the next section, we will briefly describe the occultation technique and list a few accomplishments. In Sect. 3, we will discuss the results obtained by occultations in the study of planet, planetoid and satellite atmospheres (Sects. 3.1 and 3.2), in the study of rings (Sect. 3.3) and of the Kuiper Belt (Sect. 4). In Sect. 5, we describe the instrumentation presently available and its deficiencies and outline our plan to provide a better suitable instrument for this technique.

## 2 Method of Stellar Occultations

During their motion in the sky, solar system objects may come in front of a star and occult it. Depending on size, distance and relative velocity, this occultation may last from a small fraction of second to several hours. The star may then completely disappear if the body is opaque (*a satellite*), or may be partially attenuated by an atmosphere or semi-transparent object like a ring. Because angular diameters of stars are about one milli-arcsec (mas), their disk have typical sizes of a few km when projected at outer solar system distances. This explains the success of stellar occultations in providing km-scale resolution, out of reach of other methods. In some cases, if the projected stellar diameter is smaller than 1 km (corresponding to hotter—i.e. bluer—and fainter stars), then the resolution is eventually limited by the so-called Fresnel scale,  $L_F \approx \sqrt{\lambda D}/2$ , where  $\lambda$  is the observation wavelength and  $D$  the distance of the observer to the occulter, so that  $L_F \sim 1$  km for objects at  $\sim 30$  AU observed in visible bands. The velocity of the occulting object in the sky plane relative to the target star mainly depends on the Earth velocity perpendicular to the direction of observation, and usually lies between a few to about 25 km per second. If one wishes a spatial resolution better than 1 km, the acquisition frequency must be greater than several Hz. Such high time resolution is hardly compatible with classical imaging, and instrumentation suited to those observations are rare indeed.

Since the late 1950s, stellar occultations have provided several important results on the outer solar system, in particular about rings, satellites and planetary atmospheres. Uranus's

narrow rings and Neptune's ring arcs have been discovered through occultations. Satellites like Titan, Charon, Titania, have also been explored by stellar occultations. A new challenge is now the exploration of the Kuiper Belt using this method. In fact, while Pluto has already been explored by occultations—and with surprising results (see below)—, occultations by other known KBO's are still problematical, as they are hard to predict. The first serendipitous KBO occultation was announced in 2006 (Roques et al. 2006) but still needs to be confirmed by other detections.

### 3 Exploring the Outer Solar System

#### 3.1 Atmospheres

Ground-based observations of stellar occultations proved successful in constraining atmospheric properties of planets and satellites, coming in support to interplanetary missions like Galileo, Huygens and New Horizons. They allow us to probe planetary atmospheres at pressure ranging from a fraction of microbar to a fraction of millibar. Vertical spatial resolution can reach kilometric levels or better. In some case, even if atmospheres are not detected, stringent upper limits can be derived (Sicardy et al. 2006a; Widemann et al. 2009).

Occultations allow us to retrieve, via *inversion procedures* (see Vapillon et al. (1973) for description of the method), the temperature profiles, detect density, pressure and temperature fluctuations (thought to be caused by internal gravity waves or local inversion layers), measure haze opacities at various wavelengths and in some cases—when a *central flash* (cf below) is observed—, to derive zonal wind profiles. Note that pressure ranges of  $\mu\text{bar}$ – $\text{mbar}$  are usually difficult to observe using other techniques (and even with spacecraft, except with an in situ probe), as visible and IR instruments tend to probe deeper layers, while UV instruments are sensitive to higher regions.

Among highlights concerning atmospheres, we may quote the discovery of Pluto's tenuous atmosphere (see Yelle and Elliot (1997) for a review), and the recent detection of a major two-fold surge in pressure of the planet atmosphere between 1988 and 2002 (Elliot et al. 2003; Sicardy et al. 2003). This increase might be explained by complex seasonal effects at Pluto's surface, which permit massive nitrogen ice sublimation in spite of Pluto's recession from the Sun, causing a global cooling of the surface, that should inhibit such sublimation (Hansen and Paige 1996).

Another unique result of stellar occultations is a detailed probing of propagating waves in remote planetary atmospheres. For instance, a Titan occultation observed in 1989 allowed us to retrieve spectra, aspect ratios and amplitudes of inertia gravity waves in the satellite stratosphere (Sicardy et al. 1999). Similar gravity waves have been detected in very different atmospheres such as Jupiter's (French et al. 1974), Neptune's (Roques et al. 1994) and even Pluto's (Sicardy et al. 2003; Person et al. 2008; McCarthy et al. 2008).

Another example is given by two stellar occultations by Titan observed on November 14, 2003, which probed the satellite upper stratosphere with unprecedented km-resolution. The light curves revealed a sharp inversion layer at  $515 \pm 6$  km altitude (1.5 microbar level), with a 15 K temperature increase in only 6 km, confirmed 14 months later by the Huygens HASI instrument during the probe entry in Titans atmosphere (Fulchignoni et al. 2005). The data were also used by the Huygens project to bring additional density constraints in the maximum deceleration altitude range of ESAs Huygens probe (245–600 km altitude, or 250  $\mu\text{bar}$ –1 nbar).

In some rare cases, a central flash may be observed during an occultation, when the observer passes at some tens of km from the shadow center. Atmospheric refraction then focuses the stellar rays, causing a many-fold increase of the stellar flux. The shape of that flash is extremely sensitive to the shape of the focusing layer, which in turns depends on the zonal wind regime, i.e. E–W wind regime as a function of latitudes. Thoses zonal wind were derived for Titan in 1989 (Hubbard et al. 1993), revealing a superotation of the stratosphere near southern latitudes. The swapping of this superotation towards northern latitudes was further demonstrated using a new occultation in 2003. The 1989–2003 interval corresponds to half a Titanian year so that this swapping was expected (Sicardy et al. 2006b).

Finally, multi-band observations can be powerful in revealing hazes in atmospheres, as there is usually a strong wavelength dependence of haze opacities, the optical depth being higher in blue than near IR (Hubbard et al., 1993; Sicardy et al. 2006a; Zalucha et al. 2007). Those chromatic effects may help better constraining the size of the grains responsible for the absorption.

### 3.2 Satellites: from Titan to Titania

Titania is the largest uranian moon. Recent analysis of a ground-based stellar occultation constrained the diameter ( $1576.8 \pm 1.2$  km, see Widemann et al. (2009)), oblateness and density at better accuracy than obtained by the Voyager 2 mission. The occultation is used to constrain the presence of an atmosphere around Titania. As a matter of fact, near-IR spectroscopy has indicated the presence of water ice and carbon dioxide ice on the surface of Titania. While H<sub>2</sub>O ice is clearly involatile, CO<sub>2</sub> ice stability against sublimation over a seasonal cycle of Titania can be considered (Grundy et al. 2006). Analysis allowed one to put upper limits of 10–20 nbar for the surface pressure of CO<sub>2</sub>, CH<sub>4</sub> or N<sub>2</sub> atmospheres. However, at maximum temperatures given by instantaneous equilibrium with solar input, a CO<sub>2</sub> sublimation-induced atmosphere is still a factor of 3–6 lower than the upper limit provided by the analysis (Widemann et al. 2009).

### 3.3 Ring Systems

Although originally aimed at studying planetary atmospheres, stellar occultations have brought important results on ring systems surrounding the giant planet. They permitted the serendipitous discoveries of Uranus narrow rings (Elliot et al. 1977), Neptunes ring-like arcs (Hubbard et al. 1986; Sicardy et al. 1991), and the review of Porco et al. (1995), and a detailed scanning of Saturns rings from the ground (Nicholson et al. 2000, among others). A big advantage of stellar occultations when studying rings is their high spatial resolution, which is ultimately limited by Fresnel diffraction, and can allows one to reveal details as small a one km inside optical depth profiles. Even when the star diameter projected at the rings is larger the Fresnel diffraction scale, resolution better than 10 km can be achieved. This is far better than any Earth-based classical imaging methods, where resolutions are at best several hundreds of km. Beside revealing rings otherwise invisible from Earth, stellar occultations can therefore uncover subtle dynamical behavior like ring eccentricities, sharp edges and self-excited normal modes with amplitudes of a mere fraction of kilometer (see French et al. (1991) for a review). This accuracy also explains why stellar occultations are most useful to pin down the pole position of the planet they orbit, at unprecedented accuracy. This might reveal for instance a slow precession of Saturns spin axis, undetectable with other methods (Nicholson et al. 1990).

## 4 A Challenge for Occultations: The Far Outer Solar System

### 4.1 Large KBOs

Large KBOs (Eris, Quaoar, Pluto, ...) have been detected and followed by direct imaging. The farthest observed KBO is Eris, when it travelled at its perihelion, at 97 AU from the Sun. Although large objects can be studied in direct imaging, *predicted* occultations could provide more accurate information on many of the observational parameters that direct observations can. Scientific goals pursued are : (a) Get sizes and shapes at kilometric accuracy, as we already did for Charon and Titania. Elongated shapes suspected from rotational light curves *2003 EL61* can be confirmed by occultations. Current published sizes are based on visual magnitudes combined with IR thermal emission, and have accuracies of 5–20% (i.e. several tens of km), an accuracy we could improve. For those bodies with satellites, constraints on masses are available from orbital motion. Thus, accurate sizes translate into accurate densities, an important parameter to assess internal structure models (like ice/rock ratio). (b) Discover and/or monitor atmospheres around the largest KBOs as already done for Pluto. Overall, two orders of magnitude differences in pressure are expected between Plutos perihelion and aphelion, revealing a complex interplay between ices sublimation, changing solar insolation as the object revolves around the Sun, and albedo variations. (c) Scan the surroundings of these objects, in search of satellites. Probabilities are small, but such detections come for free when a campaign is organized for a given occultation. Again, kilometric accuracies would be guaranteed. This method has two specific characteristics: (1) it consists of international campaigns, involving both professional and amateur communities world-wide (see Sect. 5), and (2) it requires dedicated, compact fast photometry optical cameras, for acquisition of stellar occultation light curves.

### 4.2 Small KBOs

The occultation method can detect tiny objects, invisible in direct imaging. Occultations for these objects, obviously, cannot be predicted, and blind serendipitous campaigns shall be conducted (Roques et al. 2008). The method is successful if the density of the objects is sufficient to cause a significant number of events. If the projected stellar diameter is small enough (corresponding to bluer and fainter stars), the resolution is limited by the so-called Fresnel scale, therefore, the lightcurve of the star would show a diffraction pattern, rather than a simple extinction of flux (Roques and Moncuquet 2000; Nihei et al. 2007). Note that because diffracting patterns are distance-dependent, degeneracy between size and distance can be partially lifted and serendipitous occultations allow us to estimate the distance of the detected EKBOs (Roques et al. 2008). Several researches for occultation by KBOs have been conducted during the last years (Bickerton et al. 2008; Liu et al. 2008; Zhang et al. 2008), which allow to place upper limits on kilometer-sized objects of the Kuiper belt. Roques et al. (2006) claims the detection of hundreds-meters sized objects outside the classical Kuiper belt. If they are confirmed, these detections could be sign of a cold extended disk. the A strong limitation to these research is the existing instrumentation which is not suitable, see below. A challenging by-product would even be the first detection ever of a 2 km Oort cloud object at 5,000 AU, a feasible observation using serendipitous occultations (Nihei et al. 2007; Doressoundiram et al. 2009).

## 5 Instrumental Approaches: Present and Projects

The occultation technique has its own challenges. One of them is being able to predict occultations, in particular for the far away KBOs, knowing that the typical angular diameter on the sky is 30–100 milli-arcsec (mas), and their distance is 30–50 AU. At such distances, 1 arcsec subtends 20,000–30,000 km. So, an error of 0.1–0.3 arcsec in the body ephemeris (typical of KBOs) is enough to displace the occultation shadow track by thousands of km. The campaigns to observe the events for various sites, use both large (*VLT*) and small (1 m telescopes, or even amateur instruments down to 0.3 m). The few teams involved in such observations, mainly SWRI/Boulder, MIT and Paris teams, have developed fast and portable occultation cameras, while maintaining world-wide collaboration teams upon alert, and asking for observations on a week-time basis, once a given event is confirmed. On the other hand, the main challenges of serendipitous occultations by small KBOs are the high rate of acquisition (typically 40–100 data points/sec) connected with simultaneous observations of several targets and good photometric precision. Instruments allowing high time resolution in astrophysics in general are presently very few. Phelan et al. (2007) lists the existing instrumentation at the present time. Surveys dedicated to the KBOs research using large 2-D arrays on small telescopes, as TAOS (Lehner et al. 2009) are able to monitor thousands of stars during very long time but with poor S/N ratio. The available fast cameras on large telescopes, like Ultracam (Dhillon et al. 2007), has field of view too small to monitor more than one or two target stars, and therefore, detect too small numbers of occultations for proper statistical analysis. Multi-fibers instruments associated with fast camera allow rapid and simultaneous monitoring of several targets (Georgevits 2006). Fibers campaigns have the advantage of recording a large number of spreaded targets in a large field: In fact, the best targets for KBO research are the hottest stars, which are the fewer. Continuous readout techniques have also been applied to conventional cameras by Bianco et al. (2009).

A multi-fibres photometry instrument, UltraPhot, is proposed for the 8.2 m Very Large Telescope UT2 of the European Southern Observatory (ESO). UltraPhot will be equipped with 100 fibers for a read-out frequency of 100 Hz in 3 colors. The expected S/N ratio could be at least  $10^3/\sqrt{f}$ , where  $f$  is the read-out frequency for a magnitude 13 star. The objectives of UltraPhot concern several scientific fields beside stellar occultation, like exoplanets transits, cataclysmic variable stars or young stellar objects.

The perspective of occultations observed with the ELT will change at once the rate of events and the power of detection, i.e. the size of detectable objects. A 42 m telescope would help increasing drastically the number of occultations by known large KBO's. For instance, the gain of magnitude of such telescope is typically  $\delta_m = 3.5$  over a 8.2 m telescope. This represents a gain of more than 100 in the number of star candidates for occultations, i.e. tens of such events per year. They could be observed on alert mode and would require a minimum time, typically 30 min. Also, the Gaia mission (expected to be completed by 2016) should provide astrometric accuracy of about 25 micro arcsec for stars up to magnitude 16, while the largest known KBO's have angular diameters of more than 20 milli arcsec. Thus, differential astrometry using the GAIA catalog would permit a few mas accuracy on the occultation prediction, 'ensuring' that several occultations per year could be observed at E-ELT at some specific dates. The occultations rate of serendipitous occultations depends on the number of stars monitored with fast photometry. Then, it will depend on the field of view accessible with high time resolution. The occultation rate per star with a 42 m is typically 10 times larger than with a 8 m telescope. The outer solar system will an exciting target for the E-ELT, for instance, 1 km Oort comet as far as  $10^4$

AU will be detectable. These prospects reinforce the interest of high speed instrumentation for the E-ELT to catch the “beauty of speed” (Richichi et al. 2009).

## 6 Conclusions

Due to the serious limitations associated with the faintness of the small objects inhabiting the outer outskirts of the solar system, stellar occultations may be a promising method for exploring that region. Information about the outer solar system are in turn critical for better understanding the planet formation stage. Also, a better knowledge of the Kuiper Belt will allow us fruitful comparisons with the structure of circumstellar disks around other stars. Observations of occultations require fast photometry however, instruments adapted to high time resolution are still rare. Thus, dedicated instrumentation still need to be developed to fully take advantage of the occultation technique in particular fast photometry on large telescopes, with fibres or continuous readout techniques.

**Acknowledgments** ESO and Osservatorio Astrofisico di Arcetri are warmly thanked by F. Roques for great help during the Elba workshop. The authors acknowledge support from the french Agence Nationale pour la Recherche, under number ANR-08-BLAN-0177-01.

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