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Observation of an eclipse of U-3 Titania by U-2 Umbriel on December 8, 2007 with ESO-VLT[*]
(Research Note)

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ABSTRACT

Context. Equinox occurred on Uranus in 2007, allowing unique observations of mutual events of the satellites that occur every 42 years. On December 8, 2007, we observed an eclipse of Titania U-3 by Umbriel U-2.

Aims. Our goal was to record an observation of very high accuracy in order to evaluate the quality of the available dynamical models of the motion of the satellites.

Methods. Such an observation is challenging because of the faintness of the satellites, the vicinity of the bright planet Uranus, and the small amplitude of the magnitude drop observable during the eclipse. We recorded the event in K-band, using the ESO Very Large Telescope in Chile equipped with the NACO adaptive optics camera.

Results. High signal/noise ratio images were obtained for the event making possible the determination of relative positions of the involved satellites. Comparing our results with theoretical models of the satellites motions, we obtain a valuable assessment of the accuracy of those models.

Conclusions. Such observations provide important constraints on the orbits of the satellites. We discuss what is needed to improve existing dynamical models of the Uranian satellite system.

Key words. eclipses – planets and satellites: general

1. Introduction

Observations of mutual events among Jovian and Saturnian satellites have been performed for many years, and have shown their superiority over direct astrometric satellite observation. Because of the photometric nature of those observations, their accuracy is directly translated into distance at Uranus – and not into geocentric angles. Thus, what was good for Jupiter and Saturn should be even better for Uranus. For instance, an accuracy of 30 km near Jupiter corresponds to an angular accuracy of 10 mas. Near Saturn the accuracy becomes 5 mas and near Uranus, 2 mas (1 arcsec = 14 600 km).

2. Equinox on Uranus

2.1. Mutual events

Equinox on Uranus occurs only every 42 years, when the Sun crosses Uranus' equatorial plane, which coincides with the orbital plane of the main and inner satellites. Under these circumstances, the satellites may eclipse each other. Since Earth appears to be angularly very close to the Sun as seen from Uranus, it also crosses the planet equatorial plane near equinox. In 2007, the Sun went through Uranus' equatorial plane on December 6, while the Earth crossed it three times because of its heliocentric motion, combined with the slow motion of Uranus. Those Earth ring plane crossings occurred on May 2, August 16, 2007 and February 20, 2008. Mutual events occurred from May 2006 to January 2009 but very few were observable: they must happen far enough (angularly) from the planet, and cause a magnitude drop deep enough to be detectable. The V-magnitudes of the Uranian satellites at opposition are as follows: 14.4 for Ariel (U-1), 15.3 for Umbriel (U-2), 13.9 for Titania (U-3), 14.2 for Oberon (U-4) and 16.5 for Miranda (U-5).

2.2. The program of observations and the instrument

On December 8, 2007, Umbriel eclipses Titania as predicted by Arlot and Lainey (2006). The event was observed with the ESO-VLT at Paranal, Chile, as part of a run dedicated to the Sun ring plane crossing (occurring on December 6, 2007), aimed at observing the unlit side of the rings and obtaining astrometric observations of the fainter inner satellites. We used the NACO instrument at the UT4 "Yepun" telescope. NACO is composed of CONICA, an Aladdin 1024 × 1024 pixel InSb near-infrared

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[*] These observations were made through the ESO run 080.C-03575 (A).

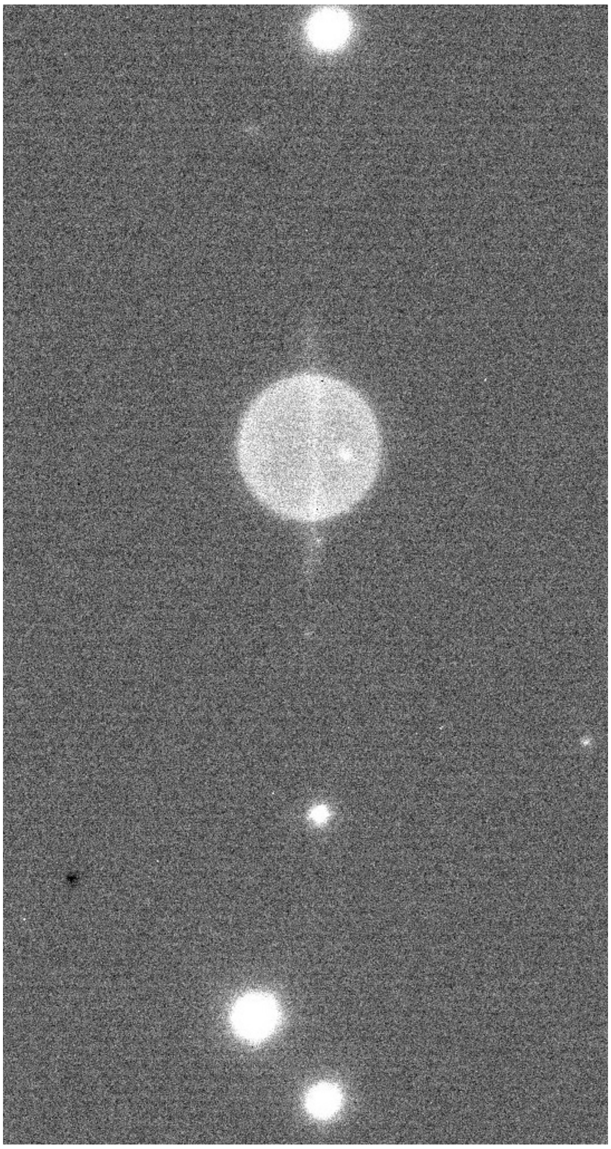

Fig. 1. A NACO image of the Uranian system. *From the top to the bottom*: Ariel, Uranus with rings and small satellites Puck and Portia, Miranda and at the bottom, Titania and Umbriel. North is up and East is left. The size of the field from North to South is 27 arcsec. The image has been rotated 14 degrees counterclockwise.

camera, and NAOS, a Shack-Hartmann-based adaptive optics (AO) system. We observed the event in K-band (2.2 micrometers) using Uranus (diameter around 3.5 arcsec) as the reference object for the visible wavefront sensor. The planet is very dark in the K band, due to methane absorption, thus avoiding scattered light from Uranus. The field of view was $27'' \times 27''$, corresponding to a pixel size of 27 mas. This scale permitted critical sampling of the point spread function of the AO-fed camera, which delivers diffraction limited images with a resolution of about 70 mas in the K band.

3. Observations and data reduction

3.1. The observation

Titania's eclipse by Umbriel started on December 8, 2007, at 1^h54^m and ended at 2^h02^m UTC. We took 166 images with 2-s exposure time each, and a cycle time of 8.5 s from $1^h46^m52^s$ to $2^h10^m21^s$. The eclipse itself covers about 60 images during the observation. Alternated offsets were applied to the field of view, in order to subtract the sky background from each image. Figure 1 shows a raw image (no treatment has been made except the substraction of the sky background) of the Uranian system at the beginning of the event.

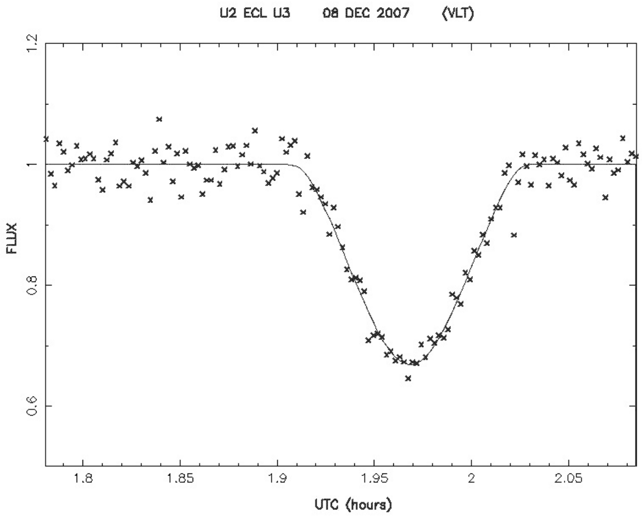

Fig. 2. The light curve of the eclipse of Titania by Umbriel.

3.2. Image processing

We measured Titania's flux using nearby Umbriel as a photometric reference, and assuming that Umbriel's flux was constant during the 5 min of the eclipse (this is reasonable because of the short duration of the eclipse compared to the rotation period of Umbriel). During the event, the seeing worsened, so that AO corrections became poorer due to those localized seeing fluctuations. Therefore, we cross-correlated Titania's image with Umbriel's profile taken at the same time, an efficient method to obtain the ratio of the two fluxes, while eliminating photometric fluctuations caused by seeing. Note that since Titania and Umbriel were only 2 arcsec apart during the event, their images have highly correlated structure, thus justifying this approach.

3.3. The light curve

Figure 2 shows the normalized light curve of the eclipse of Titania by Umbriel, after subtracting the sky background and using Umbriel as a photometric reference, as explained above. The ordinate shows Titania's flux, normalized to the full (i.e. uneclipsed) Titania flux, while the abscissae is in time unit.

4. The analysis of the light curve

Several parameters can be deduced from the light curve. However, it is not useful to fit a complete theoretical light curve to a single observation because of the number of unkown parameters which will not be fitted properly. Instead, we will deduce from this light curve the minimum distance between the satellites (in heliocentric frame) and the time of this minimum. The time of minimum flux corresponds to the minimum of apparent heliocentric distance – assuming that Titania's disk has uniform brightness and that the phase angle is zero. This is not strictly true in the present observation, mainly because of phase effects

Table 1. Photometric results from the light curve.

	Date of minimum UTC	Flux drop from 0 to 1	Impact param. in km
LJ86 calc.	$1^h55^m37^s$	0.417	425
LA06 calc.	$1^h57^m43^s$	0.218	790
Present obs.	$1^h58^m03^s$	0.304	635

that slightly move the photocenter away from the center of figure (which is assumed to be the satellite center of mass as well). At the time of event, the phase angle was near its maximum possible value of 2.8 degrees. Considering the direction of the Sun, and directions of motion for Titania and Umbriel's shadow, the phase affects mostly the intensity of the magnitude drop, rather than the time of minimum flux (Umbriel and Titania moving in the North-South direction). According to Lindegren (1977), the formulae providing shift in the photocenter center of figure are:

$$\begin{aligned}\Delta\alpha\cos\delta &= Cs\sin i/2\sin Q\\ \Delta\delta &= Cs\sin i/2\cos Q \qquad (1)\end{aligned}$$

where Q is the position angle of the equator of intensity, i the phase angle, s the radius of the body and C a coefficient depending on the scattering law.

The maximum of the phase in right ascension is, for $i = 2.8$ degrees and $Q = 90$ degrees. C may be taken as 0.75 for Titania as proposed by Lindegren (1977). According to the formula above, the displacement of the photocenter from the center of figure is:

$\Delta\alpha\cos\delta = 13$ km (corresponding to a phase defect of 26 km). We will take this into account to convert the observed magnitude drop into impact parameter.

We determined the minimum of the light curve by fitting the light curve (cf. Fig. 1) determined through our prediction program (Arlot & Lainey 2006). The error on the fitted time of the minimum and on the flux drop is deduced from the fit of an even polynomial.

The values of the relevant parameters deduced from that fit are as follows:

- time of the observed minimum of the light curve: $1^h58^m3^s$ +/– 6 s UTC;
- value of the observed flux drop: 0.327 +/– 0.017 which corresponds to an impact parameter of 585 km +/– 30 km.

We correct these values from the phase defect and we obtain an impact parameter of 635 km +/– 30 km that corresponds to 0.304 +/– 0.017 for the flux drop. Table 1 lists our observed values together with theoretical results (the theoretical flux drop is calculated without phase defect) derived from two different models: LA06 from Arlot et al. (2006), and LJ86 from Laskar and Jacobson (1987). Using a more sophisticated model (Emelianov & Gilbert 2006), the fit provides an impact parametr of 627 km +/– 12 km and the minimum time at $1^h58^m6.6^s$ (Emelianov 2008). Note the accuracy of the observation: 30 km corresponds to about 2 mas in geocentric angle. This accuracy can be compared with classical ground-based astrometry, limited to 50 mas for individual observations.

5. Comparison of the observations with the theoretical calculations, interpretation of the results

We will now compare the predictions made by two theoretical models of the motion of the satellites to the observation. The first model used is LJ86, the older one built on observations made from 1911 to 1986 and the second model is LA06 based on observations made from 1948 to 2003. We expect LA06 to predict values closer to the observation. Table 1 shows that LA06 (with a C-O of –20 s in time) is a better model for the longitudes of the satellites, probably because it is fitted to more recent observations than LJ86 (with a C–O of –146 s in time). Concerning the flux drop, the observed value lies midway between the two theoretical calculations, the O–C is 210 km for LJ86 and –155 km for LA06. It shows that the relative inclination of the satellite orbits is difficult to improve even with recent observations since most of astrometric observations have been made when the system was seen pole-on. The mutual events observations thus appear to be very useful for inclination determination since we show that the accuracy is 30 km (2 mas geocentric).

Astrometric information cannot be derived about individual satellites but one can determine a relationship between the two drifts in longitude through the following equation. We have:

$$a_2\delta l_2\cos\phi_2 - a_3\delta l_3\cos\phi_3 = (a_2n_2\cos\phi_2 - a_3n_3\cos\phi_3)\Delta T$$

where: a_2 and a_3 are the semi major axes of U-2 Umbriel and U-3 Titania; n_2 and n_3 are the mean motions of the same; ϕ_2 and ϕ_3 are the heliocentric synodic longitudes of the satellites; δl_2 and δl_3 are the shift in longitude explaining the shift of the event in time; ΔT is the C-O of the date of the minimum of flux (–146 s for LJ86 and –20 s for LA06). We obtain a relationship between the two shifts in longitude of the satellites, in degrees:

$$15\,1883.0\delta l_2 + 377\,157.626\delta l_3 = 333.21660\Delta T$$

or in kilometer units:

$$32.7155\delta l_2 + 49.52929\delta l_3 = 333.21660\Delta T.$$

If $\delta l_2 = 0$, then $\delta l_3 = 135$ km for LA06 and 982 km for LJ86 and if $\delta l_3 = 0$, then $\delta l_2 = 204$ km for LA06 and 1487 km for LJ86.

We now look forward receiving another observation of an event implying U-2 Umbriel and U-3 Titania at a different phase angle, in order to be able to solve the equation. If enough events are observed, these observations will be useful to fit theoretical models, thanks to their high accuracy.

In a recent paper, Hidas et al. (2008) reported the observation of an occultation of U-2 Umbriel by U-4 Oberon. We cannot directly compare their results with ours since different satellites are involved, but it is interesting to note that their results are similar to ours: the C-O in time is –141 s for LJ86 and –16 s for LA06. The impact parameter deduced from their observation is 500 km +/– 80 km and ours is 635 km +/– 30 km. Note that Hildas et al. (2008) refer to an occultation, which is sensitive to the relative albedos of the implied satellites, in contrast to an eclipse, where the flux drop is not dependent on the global albedos.

6. Conclusion

Our results demonstrate the high angular resolution of mutual events involving Uranian satellites. Our observations show that the new dynamical models recently published failed to provide accurate inclination of the orbits of the satellites by lack of data containing sufficient information. It may help to constrain the theoretical models thanks to its high accuracy. Observations made near the equinox time may also improve the precession of the planet Uranus through the knowledge of the inclination of their orbits. In spite of the difficulty in recording such events, we hope that additional events of this kind will be observed to gather useful information and improve theoretical models of the motions of satellites.

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