An observation of a mutual event between two satellites of Uranus

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ABSTRACT

We present observations of the occultation of Umbriel by Oberon on 4 May, 2007. We believe this is the first observed mutual event between satellites of Uranus. Fitting a simple geometric model to the lightcurve, we measure the mid-event time with a precision of 4 seconds. We assume previously measured values for the albedos of the two satellites [Karkoschka 2001], and measure the impact parameter to be 500$\pm$80 km. These measurements are more precise than estimates based on current ephemerides for these satellites. Therefore observations of additional mutual events during the 2007–2008 Uranian equinox will provide improved estimates of their orbital and physical parameters.

Key words: occultations – planets and satellites: individual: Umbriel – planets and satellites: individual: Oberon.

1 INTRODUCTION

The planetary satellite systems of the giant planets undergo seasons of mutual eclipses and occultations twice during a planet’s orbital revolution, when the Sun and the Earth respectively pass through the planet’s equatorial plane. Jovian and Saturnian mutual events have been observed since 1973 [Aksnes et al. 1984; Arlot et al. 1992, 1995; Thuillot et al. 2001] resulting in very precise measurements of the satellites’ positions from so-called “photometric astrometry” [Vasundhara et al. 2003; Novelles et al. 2003].

The Uranian system, although it resembles in many respects the Jovian and Saturnian systems, has not yet benefitted from such circumstances. The last Uranian equatorial plane crossing occurred in February 1966, well before the advent of CCD technology. The 2007–2008 Uranian equinox presents the only opportunity to observe the mutual events of the Uranian satellites until the late 2040s [Christou 2005; Arlot et al. 2006]. Apart from their value in improving the satellite ephemerides and system constants, mutual event lightcurves can provide information on large-scale albedo variations across the northern hemispheres of the satellites that were in darkness during the Voyager 2 flyby on Uranus in 1986 [Christou 2003]. Combined with Voyager 2 imagery, they may enable compilation of the first global, albeit crude, albedo maps of these bodies.

Here we report our observations and analysis of an occultation of Umbriel (Uranus II) by Oberon (Uranus IV). To our knowledge, this constitutes the first ever observation of a mutual event between two satellites of Uranus.

In Section 2, we describe our observing strategy, the equipment used and the data reduction process. In Section 3 we present the results of our lightcurve analysis. We discuss the implications of our results for Uranian satellite science in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The observations were carried out on 4 May, 2007, using the Faulkes Telescope South sited at Siding Spring, Australia and an EEV 2048x2048 CCD with a field of view of 4.6 arcmin. The configuration of the Uranian moons at the time may be seen in Fig. 1. An SDSS $i$ filter was used to minimise glare from Uranus and enhance satellite contrast. Images were binned 2x2 prior to readout resulting in an image scale of 0.27 arcsec per pixel. The field was centred at Uranus and 3-sec exposures were acquired every $\sim$13 sec from 19:02 UT until 19:30 UT, resulting in a total of 150 frames.

Following bias and dark subtraction and flatfielding, a fit was performed (using pixels outside the plane occupied by the moons) to estimate the brightness of the scattered-light halo surrounding Uranus itself. After subtracting this estimated stray light, differential aperture photometry was carried out on the Umbriel-Oberon pair using Titania (Uranus III) as the reference satellite. The atmospheric seeing was poor and variable during the observation, with full width at
larger than the average photon shot noise for the same interval. The error estimates on all points were scaled up to match this larger value. The relative fluxes were normalised to have an average value of 1 outside the event.

3 Data Analysis and Interpretation

A simple geometric model of the occultation was used to fit the data. The satellites are modelled as uniformly illuminated discs with radii $R_O$ (Oberon) and $R_U$ (Umbriel). The albedo (brightness per unit disc area) of Oberon relative to that of Umbriel is $a_{O/U}$. The combined flux of the two satellites is then

$$f = 1 - \frac{A}{\pi(R_O^2 + a_{O/U}R_U^2)}$$

where

$$A = \frac{R_O^2}{2}(\theta_U - \sin \theta_U) + \frac{R_U^2}{2}(\theta_O - \sin \theta_O)$$

is the area of overlap between the two discs, with $\theta_U = 2 \cos^{-1}\left(\frac{R_U^2 + d^2 - R_O^2}{2R_Ud}\right)$ (similarly for $\theta_O$, swapping the subscripts U and O). Finally, the distance $d$ between the centres of the two satellites (projected onto the sky) at a time $t$ is given by

$$d^2(t) = x^2 + \left[v(t - t_0)\right]^2$$

where $x$ is the impact parameter (minimum value of $d(t)$), $v$ is the relative speed of the two moons in the plane of the sky, and $t_0$ is the time of maximum occultation.

The radii of the two satellites are already known to a precision better than 0.5%. Thus their values in the model were fixed to $R_U = 584.7$ km and $R_O = 761.4$ km [Thomas 1988]. The relative speed was also fixed, with a value of $v = 7.081$ km/s derived from the known orbital elements of the satellites [Giorgini et al. 1996].

The parameters to be determined from the fit are the relative albedo $a_{O/U}$, the impact parameter $x$, and the event centre time $t_0$. The effect of the first two on the shape of the lightcurve is symmetric about the event centre, while the effect of changing $t_0$ is antisymmetric. As $a_{O/U}$ and $x$ both primarily affect the depth of the signal (the latter also affects its duration), there is a strong degeneracy between the two.

Allowing all three parameters to vary in a non-linear least-squares fit (performed using CURVEFIT in IDL, with inverse-variance weights) gives the values $a_{O/U} = 0.91$, $x = 590$ km, $t_0 = 19.1645$ hours (19:09:52 UT). This is the fit over-plotted on the lightcurve in Figure 2. The value of $t_0$ is independent of the other two parameters and has a 1σ error of 4 seconds.

Figure 3 shows chi squared as a function of $a_{O/U}$ and $x$ if $t_0$ is fixed at the value above. Projecting the 1σ contour onto each axis, the measured values with formal errors are $a_{O/U} = 0.9^{+1.1}_{-0.4}$ and $x = 600^{+150}_{-450}$ km.

An estimate for the parameter $a_{O/U}$ can be derived from independent measurements. Table V of [Karkoschka 2001] lists reflectivities of the Uranian satellites measured with the Hubble Space Telescope at various phase angles and wavelengths. The effective wavelength for our observations was approximately 0.77 μm (SDSS i filter) and the phase angle
Table 1. Predicted and observed parameters of the occultation of Umbriel by Oberon on 4 May, 2007. Errors in the mid-event times and measured duration are shown in brackets, in units of seconds.

| Reference          | Ephemeris | Event Start | Mid Event | Event End | Duration (sec) | Light drop (%) |
|--------------------|-----------|-------------|-----------|-----------|----------------|----------------|
| Christou (2005)    | GUST86    | 19:04:26    | 19:07:31(60) | 19:10:36 | 371            | 0.201 (R)       |
| Arlot et al. (2006)| LA06      | 19:06:48    | 19:09:36(60) | 19:12:24 | 337            | 0.127 (R)       |
| This work          |           | 19:06:56    | 19:09:52(4)  | 19:12:48 | 352(10)        | 0.280 (1)       |

Figure 3. Chi squared as a function of impact parameter and relative albedo (Oberon / Umbriel). Contour levels correspond approximately to 1-, 2-, and 3-σ limits. The + symbol indicates the best-fit model shown in Fig. 2. The vertical lines indicate the error range on an independent estimate of the relative albedo based on data from Karkoschka (2001), and X marks the best-fit impact parameter along this line.

at the time was 2.39 degrees. Averaging the tabulated values for wavelengths of 0.63 µm and 0.87 µm (at phase angle 2.82 degrees) gives reflectivities of 0.166 ± 0.007 for Umbriel and 0.203 ± 0.009 for Oberon, and a_{O/U} = 1.2 ± 0.1. From the intersection of this error range with the 1σ contour on Fig. 3 we obtain a more precise measurement of the impact parameter, x = 500 ± 80 km. These measurements are compared to predictions (Christou 2003; Arlot et al. 2006) in Table 1.

4 DISCUSSION

We have carried out the first observation of a mutual event between two satellites of Uranus, an occultation of Umbriel by Oberon. The parameters of the occultation as estimated from the data have been compared to two different sets of predictions (Table 1). One employs GUST86, a Voyager-era ephemeris while the other makes use of the more recent LA06 ephemeris which incorporates post-1986 astrometry of the satellites.

The errors in these predictions reflect the observational uncertainties in the satellite positions used to derive said ephemerides. Typical satellite-to-satellite relative positional errors of 0.03 arcseconds (Christou 2003) translate to ~ 400 km at the distance of Uranus. For the mutual event observed here, the relative velocity of the satellites is 7 km/s, so the mid-event time predictions are uncertain by ~ 60 seconds. Also, the unusual orientation of the Uranian satellite system renders precise determination of the inclination of the orbit planes difficult when the system is pole-on to the Earth. This was the case until the early 1990s, leading to increased uncertainties in the predicted impact parameters.

We find that our observations are in closer agreement with the LA06 predictions. In this case, considering the above errors, the predicted and observed mid-times are in agreement. Using Karkoschka (2001) to fix the relative albedo between the two satellites, we estimate the impact parameter to be 500 ± 80 km or 0.036 ± 0.006 arcsec compared to a value of 0.047 arcsec predicted by LA06. The formal errors of our results are smaller than those achieved by conventional astrometry (e.g. Jones et al. 1993; Veiga and Vieira Martins 1994; Shen et al. 2004). We thus expect a considerable improvement in the ephemerides of the satellites to result from observing a large number of such events predicted to occur throughout the rest of 2007 and into 2008. This should also improve our knowledge of some poorly-known physical parameters of the system such as the masses of the inner three satellites Miranda, Ariel and Umbriel (Jacobson et al. 1992) and result in a better understanding of the Uranian system as a whole.

Finally, we note that our observations of this event do not strongly constrain the relative albedo of the two satellites. This is due to the degeneracy between the albedo and the impact parameter for a single event. This degeneracy can be lifted either by (a) simultaneous fitting of lightcurves for multiple events sampling different satellite aspects assuming good a priori knowledge of the orbits or (b) a global fit of the albedo and orbit model together. Although both problems are sensitive to noise, they do not contain fundamental degeneracies and have been successfully used in the past to derive large-scale maps of Pluto (Young et al. 1999). Such a fit can only be attempted when observations of as many events as possible have been successfully acquired. If successful, it will yield regional to hemispherical albedo information on the unimaged hemispheres of the major uranian satellites.

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