Mon. Not. R. Astron. Soc. **384,** L38–L40 (2008) doi:10.1111/j.1745-3933.2007.00418.x

An observation of a mutual event between two satellites of Uranus

M. G. Hidas,[1,2]★ A. A. Christou[3]★ and T. M. Brown[1,2]
[1]*Las Cumbres Observatory Global Telescope, 6740 Cortona Dr. Ste. 102, Goleta, CA 93117, USA*
[2]*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[3]*Armagh Observatory, College Hill, Armagh BT61 9DG*

Accepted 2007 November 12. Received 2007 November 9; in original form 2007 October 10

ABSTRACT

We present observations of the occultation of Umbriel by Oberon on 2007 May 4. We believe this is the first observed mutual event between satellites of Uranus. Fitting a simple geometric model to the light curve, we measure the mid-event time with a precision of 4 s. We assume previously measured values for the albedos of the two satellites, and measure the impact parameter to be 500 ± 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, 1997; Thuillot et al. 2001) resulting in very precise measurements of the satellites' positions from so-called 'photometric astrometry' (Vasundhara et al. 2003; Noyelles, Vienne & Descamps 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 1966 February, 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, Lainey & Thuillot 2006). Apart from their value in improving the satellite ephemerides and system constants, mutual event light curves 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 2005). 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.

★E-mail: mhidas@lcogt.net (MGH); aac@star.arm.ac.uk (AAC)

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 light curve 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 2007 May 4 using the Faulkes Telescope South sited at Siding Spring, Australia and an EEV 2048 × 2048 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. A Sloan Digital Sky Survey (SDSS) *i* filter was used to minimize glare from Uranus and enhance satellite contrast. Images were binned 2 × 2 prior to readout resulting in an image scale of 0.27 arcsec per pixel. The field was centred at Uranus and 3-s exposures were acquired every ∼13 s 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 half maximum (FWHM) between 1.6 and 3.9 arcsec, and the worst seeing occurring near the time of the occultation. A circular aperture with diameter of 8 pixels (2.16 arcsec) gave the smallest scatter in the relative light curve.

The three frames with the worst seeing (FWHM > 3.4 arcsec) resulted in clearly discrepant relative flux values. One of these occurs near the beginning of the occultation, and the other two near the

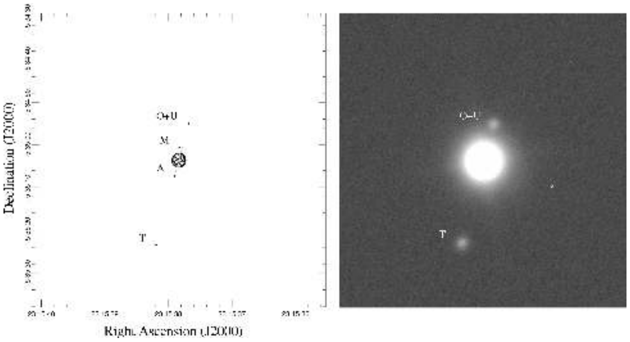

Figure 1. Predicted (left-hand panel) and observed (right-hand panel) configuration of the Uranian satellites shortly after 19:00 UT on 2007 May 4. The diagram on the left-hand panel was generated using M. Showalter's URANUS VIEWER V2.2 online visualization tool (pds-rings.seti.org/tools/viewer2_ura.html). The image on the right shows one of the frames (Frame #29) we acquired during the observations, logarithmically stretched to show the moons. Individual satellites are indicated as follows: M – Miranda, A – Ariel, U – Umbriel, T – Titania, O – Oberon. At the time, the Umbriel/Oberon pair was at a distance of 9 arcsec from the centre of Uranus. Ariel and Miranda are at 4 arcsec and hidden in the planet's glare.

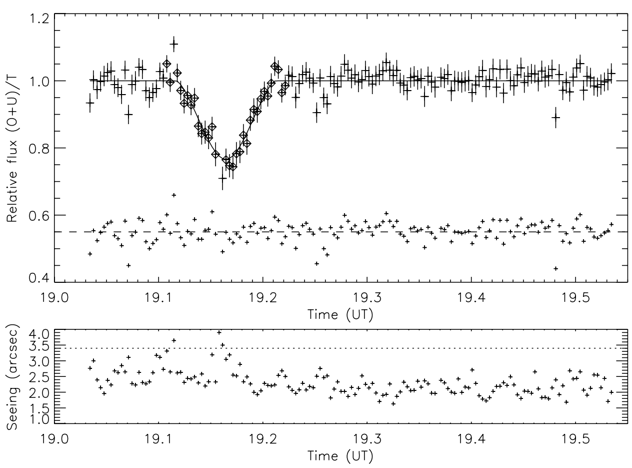

Figure 2. Light curve of the mutual event. Upper panel: the combined flux of Oberon and Umbriel relative to Titania as a function of Universal Time on 2007 May 4. Diamonds indicate the points used in the fit. Also shown are the best-fitting model from CURVEFIT (solid curve) and residuals ('+' symbols). Lower panel: estimate of the image full-width at half maximum corresponding to each data point. The three points above the dotted line (3.4 arcsec) were not included in the fit.

centre of it. These points have been excluded from further analysis. The light curve and seeing variations can be seen in Fig. 2.

Excluding the section during occultation, the relative flux time-series shows a 1σ scatter of 0.03, which is 36 per cent 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 normalized 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 $R_{\rm O}$ (Oberon) and $R_{\rm U}$ (Umbriel). The albedo (brightness per unit disc area) of Oberon relative to that of Umbriel is $a_{\rm O/U}$. The combined flux of the two satellites is then

$$f = 1 - \frac{A}{\pi\left(R_{\rm U}^2 + a_{\rm O/U} R_{\rm O}^2\right)} \tag{1}$$

where

$$A = \frac{R_{\rm U}^2}{2}(\theta_{\rm U} - \sin\theta_{\rm U}) + \frac{R_{\rm O}^2}{2}(\theta_{\rm O} - \sin\theta_{\rm O}) \tag{2}$$

is the area of overlap between the two discs, with

$$\theta_{\rm U} = 2\cos^{-1}\left(\frac{R_{\rm U}^2 + d^2 - R_{\rm O}^2}{2R_{\rm U}d}\right) \tag{3}$$

(similarly for $\theta_{\rm O}$, swapping the subscripts U and O). Finally, the distance d between the centres of the two satellites (projected on to the sky) at a time t is given by

$$d^2(t) = x^2 + [v(t - t_0)]^2 \tag{4}$$

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 the two satellites are already known to a precision better than 0.5 per cent. Thus their values in the model were fixed to $R_{\rm U} = 584.7$ km and $R_{\rm O} = 761.4$ km (Thomas 1988). The relative speed was also fixed, with a value of $v = 7.081$ km s^{-1} 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 $a_{\rm O/U}$, the impact parameter x, and the event centre time t_0. The effect of the first two on the shape of the light curve is symmetric about the event centre, while the effect of changing t_0 is antisymmetric. As $a_{\rm O/U}$ 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 $a_{\rm O/U} = 0.91$, $x = 590$ km, $t_0 = 19.1645$ h (19:09:52 UT). This is the fit over-plotted on the light curve in Fig. 2. The value of t_0 is independent of the other two parameters and has a 1σ error of 4 s.

Fig. 3 shows chi-squared as a function of $a_{\rm O/U}$ and x if t_0 is fixed at the value above. Projecting the 1σ contour on to each axis, the

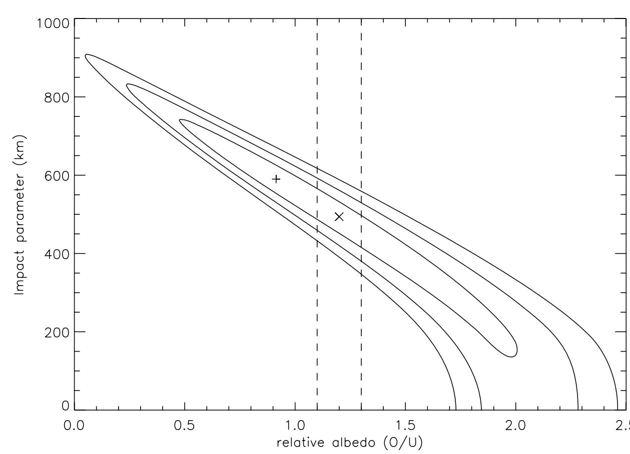

Figure 3. Chi-squared as a function of impact parameter and relative albedo (Oberon/Umbriel). Contour levels correspond approximately to 1, 2 and 3σ limits. The '+' symbol indicates the best-fitting model shown in Fig. 2. The vertical lines indicate the error range on an independent estimate of the relative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

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 (s)	Light drop (per cent)
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 (I)

measured values with formal errors are $a_{\mathrm{O/U}} = 0.9^{+1.1}_{-0.4}$ and $x = 600^{+150}_{-450}$ km.

An estimate for the parameter $a_{\mathrm{O/U}}$ 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 at the time was 2°.39. Averaging the tabulated values for wavelengths of 0.63 and 0.87 μm (at phase angle 2°.82) gives reflectivities of 0.166 ± 0.007 for Umbriel and 0.203 ± 0.009 for Oberon, and $a_{\mathrm{O/U}} = 1.2 \pm 0.1$. From the intersection of this error range with the 1σ contour on Fig. 3 we obtain a more precise measurement of the impact parameter, $x = 500 \pm 80$ km. These measurements are compared to predictions (Christou 2005; 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 arcsec (Christou 2005) 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^{-1}, so the mid-event time predictions are uncertain by ∼60 s. 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, Taylor & Williams 1998; Veiga & Vieira Martins 1999; Shen et al. 2002). 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 (i) simultaneous fitting of light curves for multiple events sampling different satellite aspects assuming good a priori knowledge of the orbits or (ii) 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.

ACKNOWLEDGMENTS

Astronomical research at the Armagh Observatory is funded by the Northern Ireland Department of Culture, Arts and Leisure (DCAL).

REFERENCES

Aksnes K., Franklin F. A., Millis R., Birch P., Blanco C., Catalano S., Piironen J., 1984, AJ, 89, 280
Arlot J.-E., Lainey V., Thuillot W., 2006, A&A, 456, 1173
Arlot J.-E. et al., 1992, A&ApSS, 92, 151
Arlot J.-E. et al., 1997, A&ApSS, 125, 399
Christou A. A., 2005, Icarus 178, 171
Giorgini J. D. et al., 1996, Bull. Am. Astron. Soc., 28, 1158
Jacobson R. A., Campbell J. K., Taylor A. H., Synnott S. P., 1992, AJ, 103, 2068
Jones D. H. P., Taylor D. B., Williams I. P., 1998, A&ApSS, 130, 77
Karkoschka E., 2001, Icarus 151, 51
Noyelles B., Vienne A., Descamps P., 2003, A&A, 401, 1159
Shen K. X., Qiao R. C., Harper D., Hadjifotinou K. G., Liu J. R., 2002, A&A, 391, 775
Thomas P. C., 1988, Icarus, 73, 427
Thuillot W. et al., 2001, A&A, 371, 343
Vasundhara R., Arlot, J-E., Lainey V., Thuillot W., 2003, A&A, 410, 337
Veiga C. H., Vieira Martins R., 1999, A&ApSS, 138, 247
Young E. F., Galdamez K., Buie M. W., Binzel R. P., 1999, AJ, 117, 1063

This paper has been typeset from a TEX/LATEX file prepared by the author.