CCD Photometry of Uranian and Saturnian Mutual Events in 2007, 2008 and 2009

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Abstract

We present a set of observations of mutual events between satellites of the outer planets Uranus and Saturn. These were made at the Ellinogermaniki Agogi School Observatory (EAO) in Pallini, Greece, using a 40 cm instrument, during the period 2007-2009. Following a successful detection of a mutual occultation between the Uranian satellites Oberon and Umbriel in 2007 (Christou et al, A&A, 2009), we observed and reduced three mutual events between the Saturnian satellites Enceladus, Tethys, Dione and Rhea in late 2008 and in mid 2009.

Introduction

The orbits of the satellites of the major planets change over time due to the gravitational attraction between the satellites and between a given satellite and the body of the planet itself. For example, a satellite raises a tidal "bulge" on the planet, which, in turn, affects the motion of that satellite by expanding or contracting its orbit. This amounts to a very small so-called "tidal" or "secular" acceleration in the satellite's orbital motion that accumulates to become an observable effect over periods of several decades or centuries. Detecting these subtle changes requires not only very accurate satellite astrometry but also regular measurements over very long periods of time. The latter requirement generally precludes the use of spacecraft data for this purpose. Accurate timing and photometry of mutual satellite events, on the other hand, is intrinsically a much better estimator of long-term orbital variation.

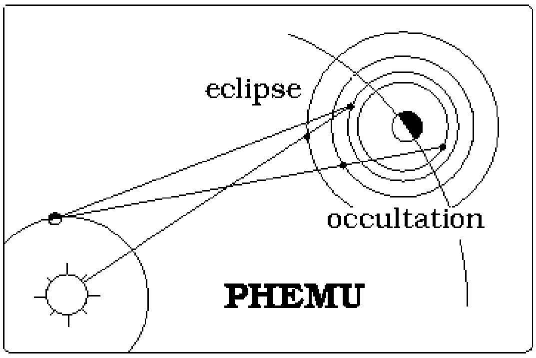


Figure 1: Geometry of the mutual events. Source: PHEMU Tech. Note #1, IMCCE, France.

The Mutual Events - IMCCE

In 2008-2010, a series of eclipses and occultations occurred among the satellites of Jupiter and Saturn due to the equinox on these planets in 2009 (Fig. 1). In 2006-2010 a similar series of astronomical events took place between the satellites of the planet Uranus. Observations of this kind were first made in 1973 for Jovian

(Aksnes & Franklin 1976), in 1980 for Saturnian (Aksnes *et al* 1984) and in 2007 for Uranian satellites (Christou et al 2009). The observation of these events provides valuable data to the professional astronomy community. As there is practically no atmosphere around the satellites, the astrometric accuracy for the satellite position can be better than 30 mas (milli-arc-seconds) for Jupiter's satellites (Arlot et al 1997) and better than 5 mas for Saturn's satellites (Noyelles *et al* 2003). These numbers suggest 90 km accuracy for the actual position of Jovian satellites in space and just 30 km for Saturnian satellites. The Institut de Méchanique Céleste et des Calcul des Éphémérides (IMCCE, formerly Bureau des Longitudes) has been organizing observing campaigns of these events since 1973 with the objective of providing the long time series necessary to isolate these tidal effects and use them as proxies for the interior of these bodies, effectively doing geophysics through ground-based photometry. IMMCE has organized the campaigns PHEURA07 for Uranian, PHESAT09 for Saturnian and PHEMU09 for Jovian satellites
(See: http://www.imcce.fr/en/observateur/campagnes_observation.php).
The dates of oppositions, conjunctions with the Sun and equinoxes of Uranus, Jupiter and Saturn are presented in table 1.

Phenomenon	**Uranus (2007)**	**Jupiter (2009)**	**Saturn (2009)**
Opposition	September 9	August 14	March 9
Conjunction with the Sun	March 5	January 24	September 18
Transit of the Sun in the equatorial plane of the planet (equinox)	December 7	June 22	August 12
Transit of the Earth in the equatorial plane of the planet (disappearance of the rings)	May 2 & August 16	April 15	September 4
Declination of the planet	-4.1 to 0 deg.	-20 to -13 deg.	0 to 8 deg.

Table 1: Dates of oppositions, conjunctions with the Sun and equinoxes of Uranus (for the year 2007), Jupiter and Saturn for the year 2009. Source: http://www.imcce.fr/fr/presentation/equipes/GAP/travaux/phemu09/index_en.html, IMCCE.

A. Observation of the Uranian mutual events (2007)

Our observations were part of a series of observations organized by Apostolos Christou during the planet's Equinox in 2007. Five different instruments worldwide had taken part in this set of observations, ranging in aperture from 0.4m to 10m. The observations covered specific intervals of time when mutual eclipses and occultations were predicted. Two of these instruments, both of 0.4m aperture, operated in Greece. On August 14th 2007 we carried out a successful observation of Uranian mutual event 2O4P from Ellinogermaniki Agogi Observatory, in which Umbriel partially occulted Oberon. Later, on September 22nd 2007, a second attempt was made to observe the event 1E5P, in which Ariel partially eclipsed Miranda, from Gerostathopoulion observatory, near Athens. However, the high air mass and poor atmospheric conditions during the observation did not allow the collection of useful data.

A1. Method & Equipment

The observation of the event 2O4P was carried out at Ellinogermaniki Agogi Observatory with a 40 cm f/10 telescope. For CCD imaging we used an ATIC 16-HR camera, set at 1x1 binning mode (see table 3 for camera specs). Image scale was 0.31 arcsec/pixel. Exposure time was 30 sec. We took 34 CCD frames in the near-infrared part of the spectrum to mitigate against the glare from the planet. UT time of first exposure was 01:09:39 and UT time of last exposure was 01:46:14. Following modeling and subtraction of the planetary source from these frames, differential aperture photometry was carried out on the satellite pair Umbriel & Oberon, involved in the event. Nearby bright satellite Titania was used as reference source.

A2. Results.

The light curve was model-fitted to yield best estimates of the time of maximum flux drop and the impact parameter. Time of mid-event was estimated to be UT 01:34:25 ± 28 sec. Impact parameter was estimated as 750 km ± 160 km (see table 2).

Date (DD/MM/YY)	**Event Type**	**Obs. Site**	**Midtime (UT)**	**Impact Parameter (km)**	**Albedo Ratio**	**Relative Speed on Impact Plane (km/sec)**	**Mean RMS on fit**
14/08/07	2O4P	Ellinogermaniki Agogi Obs. Pallini, Greece	01:34:25 ± 28	750 ± 160	0.813 ± 0.1	5.765	0.083

Table 2: Best-fit estimates of the parameters of the mutual event 2O4P for ATH1 observation (source: Christou et al, A&A 2009)

B. Observation of the Saturnian mutual events (2008 and 2009)

On the IMCCE web page there are interactive tools where one can input values for parameters (filters) e.g.: site coordinates, minimum distance of satellite from the planet, minimum planet elevation, maximum sun elevation, minimum flux drop, etc, in order to create a table of events visible from his observing site and observable according to his equipment capabilities.
(See: http://www.imcce.fr/page.php?nav=en/observateur/campagnes_obs/phesat09/prog_interactif.php)
For Athens, Greece, the number of all the theoretically visible events was 19. Many of these events were practically impossible to observe, as they occurred during bright twilight (table 4). After careful examination of this list, we selected two events to observe in 2008 and one in 2009; event 4O5P (occultation of Rhea by Dione on December 19th 2008), event 3O2P (occultation of Enceladus by Tethys on December 24th 2008 and event 3E4P (eclipse of Dione by Tethys on July 7th 2009). Next, we studied the satellite motions during these events using Starry Night software and Saturn Viewer software, which is available at http://pds-rings.seti.org/tools/viewer2_sat.html.

B1. Equipment

The telescope we used is Ellinogermaniki Agogi School's (EA) Meade LX-200R Schmidt – Cassegrain 16" (40 cm) telescope, which is located in a 5 meter dome in the area of Pallini, southeast of the city of Athens.

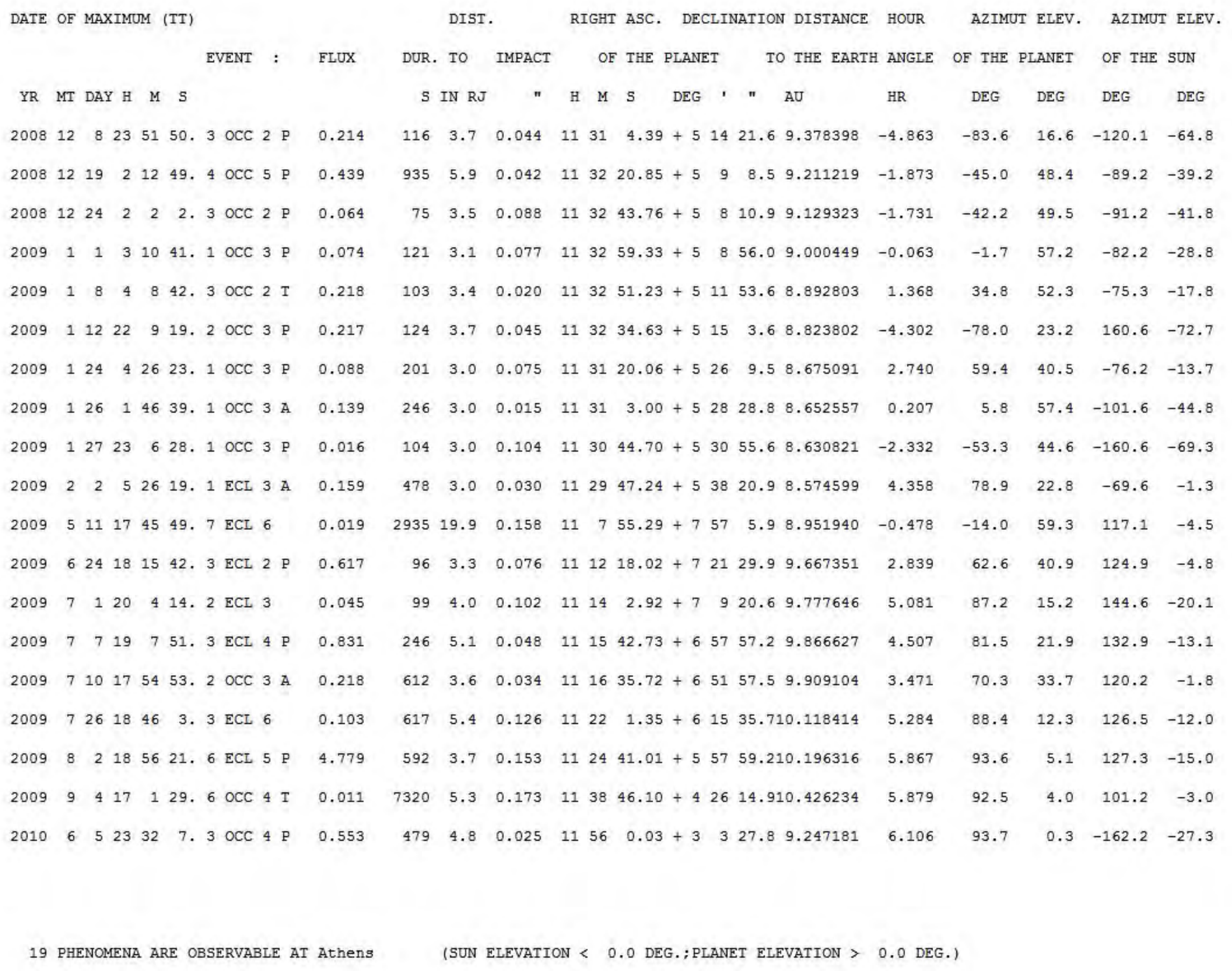
We used the ATIK 16-HR CCD camera, which has the following technical specifications (table 3):

Chip	Sony Chip ICX-285 AL
Resolution	1390 x 1040 pixels (1.445.600 pixels)
Chip size	10.2mm x 8.3mm - diagonal 13.15mm
Pixel size	6.45 x 6.45 um
Digitization	16 BIT
Computer Port	USB 1.1 Download time max. 15s
Cooling	Peltier cooling (25° below ambient temp.)
Preview function	Only approx. 1 second download time
Power supply	12V DC - 0.8A power consumption
Protective glass	Optical glass - BK-7

Table 3: CCD specifications

B2. Spectral Region

Our previous observational experience of imaging the uranian mutual event 2O4P in 2007 (Christou et al, 2009) suggested that we should make the observations in the near infrared part of the spectrum in order to minimize the glare from the bright planet. This proved to be particularly useful for the observation of the first two events, 4O5P and 3O5P. However, the prediction for the third event, (large magnitude drop, relatively large distance of target satellites from the planet) allowed us to observe the event 3E4P at the visible part of the spectrum.



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DATE OF MAXIMUM (TT)                              DIST.        RIGHT ASC.  DECLINATION DISTANCE  HOUR     AZIMUT ELEV.   AZIMUT ELEV.

                     EVENT  :    FLUX     DUR. TO   IMPACT     OF THE PLANET     TO THE EARTH ANGLE  OF THE PLANET   OF THE SUN

 YR  MT DAY H  M  S                          S IN RJ      "   H  M  S     DEG  '  "    AU         HR       DEG     DEG     DEG      DEG

2008 12  8 23 51 50. 3 OCC 2 P   0.214     116  3.7  0.044  11 31  4.39 + 5 14 21.6 9.378398  -4.863   -83.6   16.6  -120.1  -64.8

2008 12 19  2 12 49. 4 OCC 5 P   0.439     935  5.9  0.042  11 32 20.85 + 5  9  8.5 9.211219  -1.873   -45.0   48.4   -89.2  -39.2

2008 12 24  2  2  2. 3 OCC 2 P   0.064      75  3.5  0.088  11 32 43.76 + 5  8 10.9 9.129323  -1.731   -42.2   49.5   -91.2  -41.8

2009  1  1  3 10 41. 1 OCC 3 P   0.074     121  3.1  0.077  11 32 59.33 + 5  8 56.0 9.000449  -0.063    -1.7   57.2   -82.2  -28.8

2009  1  8  4  8 42. 3 OCC 2 T   0.218     103  3.4  0.020  11 32 51.23 + 5 11 53.6 8.892803   1.368    34.8   52.3   -75.3  -17.8

2009  1 12 22  9 19. 2 OCC 3 P   0.217     124  3.7  0.045  11 32 34.63 + 5 15  3.6 8.823802  -4.302   -78.0   23.2   160.6  -72.7

2009  1 24  4 26 23. 1 OCC 3 P   0.088     201  3.0  0.075  11 31 20.06 + 5 26  9.5 8.675091   2.740    59.4   40.5   -76.2  -13.7

2009  1 26  1 46 39. 1 OCC 3 A   0.139     246  3.0  0.015  11 31  3.00 + 5 28 28.8 8.652557   0.207     5.8   57.4  -101.6  -44.8

2009  1 27 23  6 28. 1 OCC 3 P   0.016     104  3.0  0.104  11 30 44.70 + 5 30 55.6 8.630821  -2.332   -53.3   44.6  -160.6  -69.3

2009  2  2  5 26 19. 1 ECL 3 A   0.159     478  3.0  0.030  11 29 47.24 + 5 38 20.9 8.574599   4.358    78.9   22.8   -69.6   -1.3

2009  5 11 17 45 49. 7 ECL 6     0.019    2935 19.9  0.158  11  7 55.29 + 7 57  5.9 8.951940  -0.478   -14.0   59.3   117.1   -4.5

2009  6 24 18 15 42. 3 ECL 2 P   0.617      96  3.3  0.076  11 12 18.02 + 7 21 29.9 9.667351   2.839    62.6   40.9   124.9   -4.8

2009  7  1 20  4 14. 2 ECL 3     0.045      99  4.0  0.102  11 14  2.92 + 7  9 20.6 9.777646   5.081    87.2   15.2   144.6  -20.1

2009  7  7 19  7 51. 3 ECL 4 P   0.831     246  5.1  0.048  11 15 42.73 + 6 57 57.2 9.866627   4.507    81.5   21.9   132.9  -13.1

2009  7 10 17 54 53. 2 OCC 3 A   0.218     612  3.6  0.034  11 16 35.72 + 6 51 57.5 9.909104   3.471    70.3   33.7   120.2   -1.8

2009  7 26 18 46  3. 3 ECL 6     0.103     617  5.4  0.126  11 22  1.35 + 6 15 35.710.118414   5.284    88.4   12.3   126.5  -12.0

2009  8  2 18 56 21. 6 ECL 5 P   4.779     592  3.7  0.153  11 24 41.01 + 5 57 59.210.196316   5.867    93.6    5.1   127.3  -15.0

2009  9  4 17  1 29. 6 OCC 4 T   0.011    7320  5.3  0.173  11 38 46.10 + 4 26 14.910.426234   5.879    92.5    4.0   101.2   -3.0

2010  6  5 23 32  7. 3 OCC 4 P   0.553     479  4.8  0.025  11 56  0.03 + 3  3 27.8 9.247181   6.106    93.7    0.3  -162.2  -27.3



  19 PHENOMENA ARE OBSERVABLE AT Athens       (SUN ELEVATION <  0.0 DEG.;PLANET ELEVATION >  0.0 DEG.)
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Table 4: The list of all 19 Saturnian mutual events potentially observable at Athens, Greece. Most of them were practically impossible to observe.
Source: http://www.imcce.fr/page.php?nav=en/observateur/campagnes_obs/phesat09/prog_interactif.php

B3. Timing.

As it is very important to have an accurate time base in capturing the mutual events, we synchronized our laptop clock with an Oregon Scientific RMB 899P DCF77 radio clock.

B4. Method of Observation

The CCD imaging of the two events 4O5P and 302P was made with the 16” Meade LX200-R telescope at the EA Observatory. For each event, CCD imaging was done with a Bessell I(s) photometric filter. For image capture we used the Artemis CCD software, which is available with the ATIK 16-HR camera. Binning mode 3X3 was used during capturing. The combination of the specific telescope and CCD imager resulted in a pixel scale of 0.93 arcsec/pixel and a FOV of 6,68 x 5,37 arcmin for each frame. For the event 4O5P we acquired 63 frames of 30 sec exposure time between UT 01:51:20 and UT 2:25:26 (19 Dec 08) and for the event 3O2P we acquired 51 frames of 6 sec exposure time between UT 01:57:12 and UT 02:04:42 (24 Dec 08). During the event 3E4P, we acquired 140 4-sec exposures between 19:00:34 UT and 19:12:52 UT. A Bessell V photometric filter was used.

B5. Image Processing with AIP4WIN V2

We derived lightcurves of the target satellite or pair of satellites with respect to a reference source by means of differential photometry (figure 2). For the first two event in December 2008, cases the reference source was satellite Titan, while Rhea was used for the third event. In the case of 3O2P in particular, we used satellite Dione as a check source.

Figure 2: Differential photometry with AIP4WINV. Left: Event 4O5P. The variable light source (V) is the satellite pair Dione+Rhea and the comparison light source (C1) is Titan. Right: Event 3O2P. The variable light source (V) is the satellite pair Tethys+Enceladus and the comparison light source (C1) is Titan. The check light source is satellite Dione (C2).

For the event 4O5P we set the radii of the photometric apertures to 9 pixels for the inner ring (the annulus containing all of the star’s light), 12 pixels for the middle ring (the inner boundary of the region containing the sky background) and 16 pixels for the outer ring (the outer boundary of the region containing the sky background). For the event 3O2P, due to the close proximity of the target to the planet Saturn and, after some trial and error, we finally set the radii of the photometric apertures to 5 pixels for the inner, 6 pixels for the middle and 8 pixels for the outer ring, in order to get reasonable results.

B6. Processing of photometric points with IDL software - Results

One of us (AAC) used Interactive Data Language (IDL) for the model fitting of the observed light curves. We estimated the time of minimum t_{min} and the impact parameter b (see figure 3) for each event by processing the light curves produced with AIP4WIN. The impact parameter b is the minimum distance between the centres of the two satellites during the event. The results are presented in table 6 and can be compared to the predicted values of the main prediction models, TASS (Vienne and Duriez 1995) and D93 (Dourneau 1993), given in table 5. Figures 4, 5 and 6 present the best-fit model vs. observations.

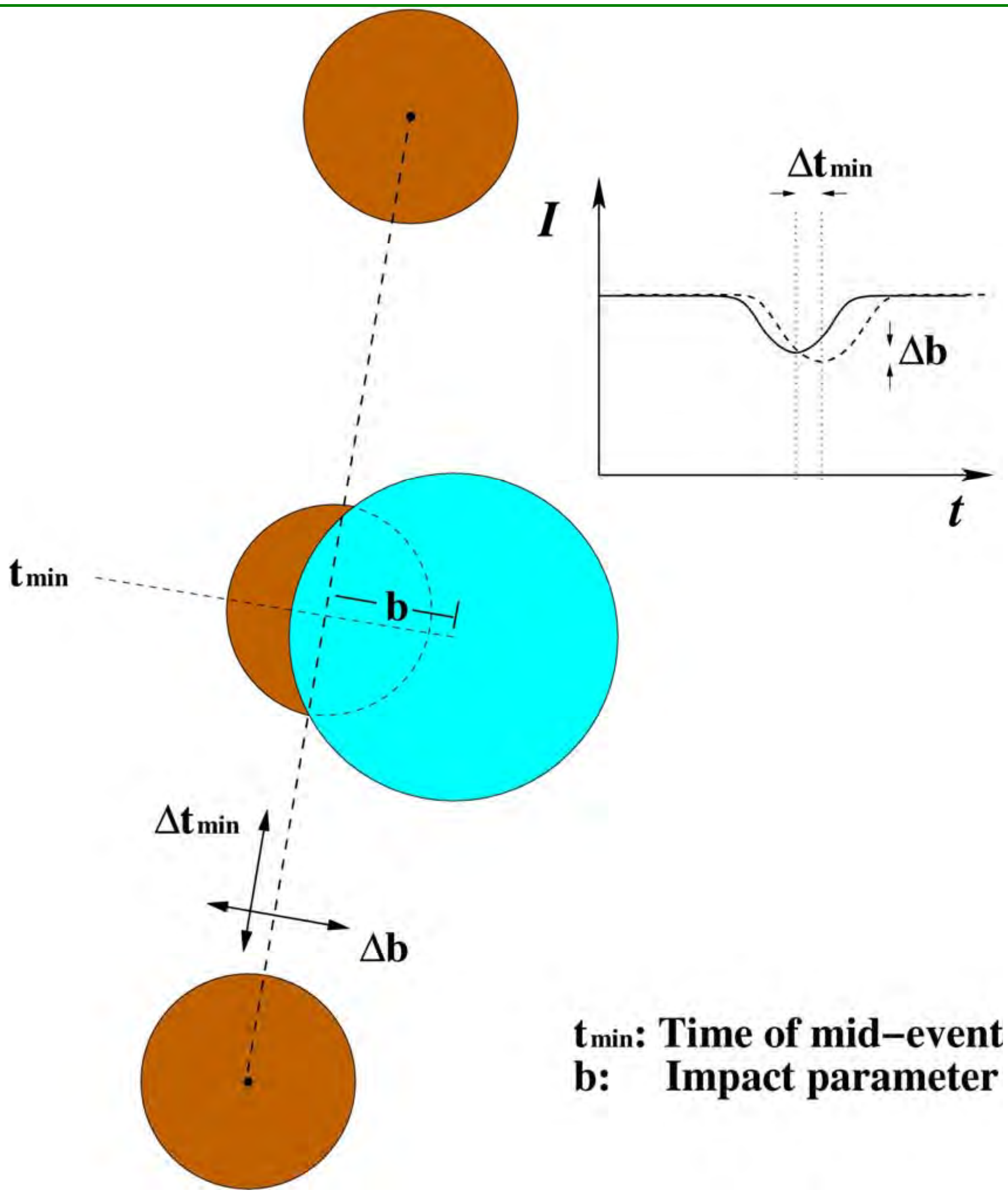

Figure 3: This diagram explains the geometry of the events. The blue disc of a satellite is occulting the brown disc of another satellite. The blue disc is larger than the brown satellite in this example, but it could be smaller. For each event there is an uncertainty Delta b in the impact parameter b (b affects how large the light drop is), and in the time of mid-event t_min. Indeed the fact that there is an a priori uncertainty in these quantities is one reason why it is valuable to do the observations.

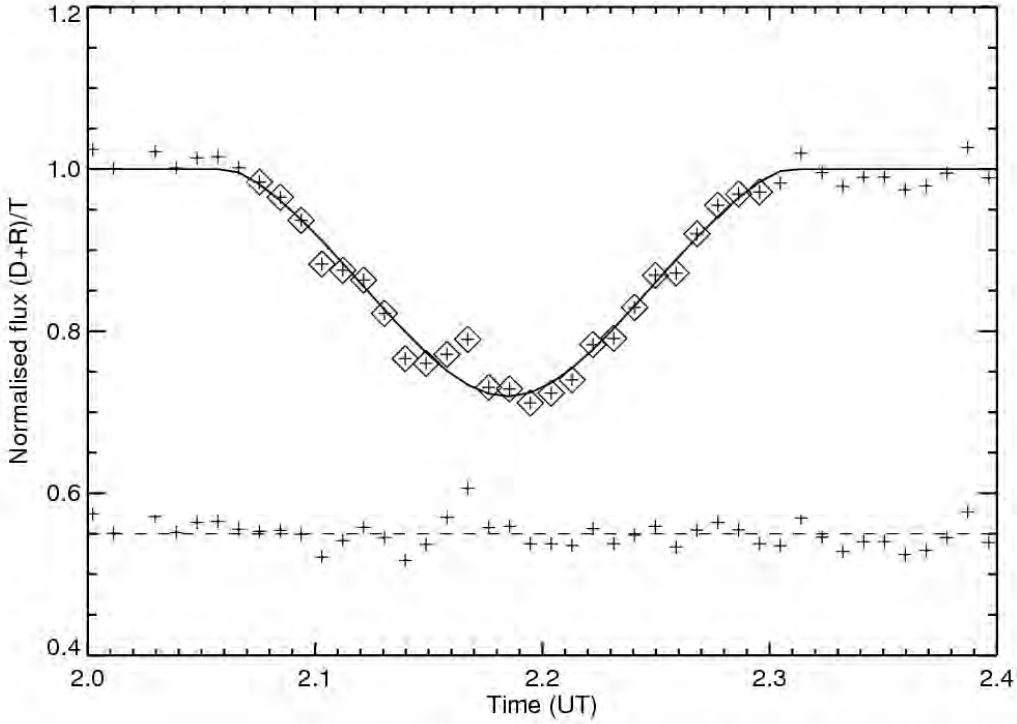

Figure 4: Best-fit model (continuous line) for the event 4O5P vs. observations (+ signs). The diamonds (◊ signs) indicate the observations, which were used for the fit. The + signs below and above the dashed line indicate the residuals after the fit.

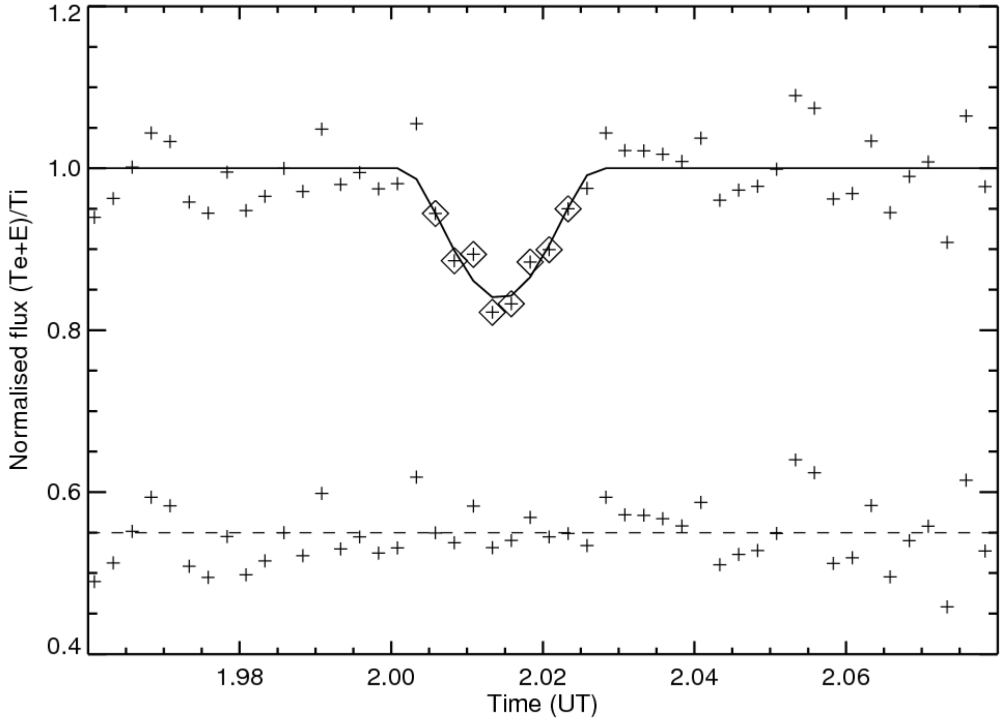

Figure 5: Best-fit model (continuous line) for the event 3O2P vs. observations (+ signs). The diamonds (◊ signs) indicate the observations, which were used for the fit. The + signs below and above the dashed line indicate the residuals after the fit.

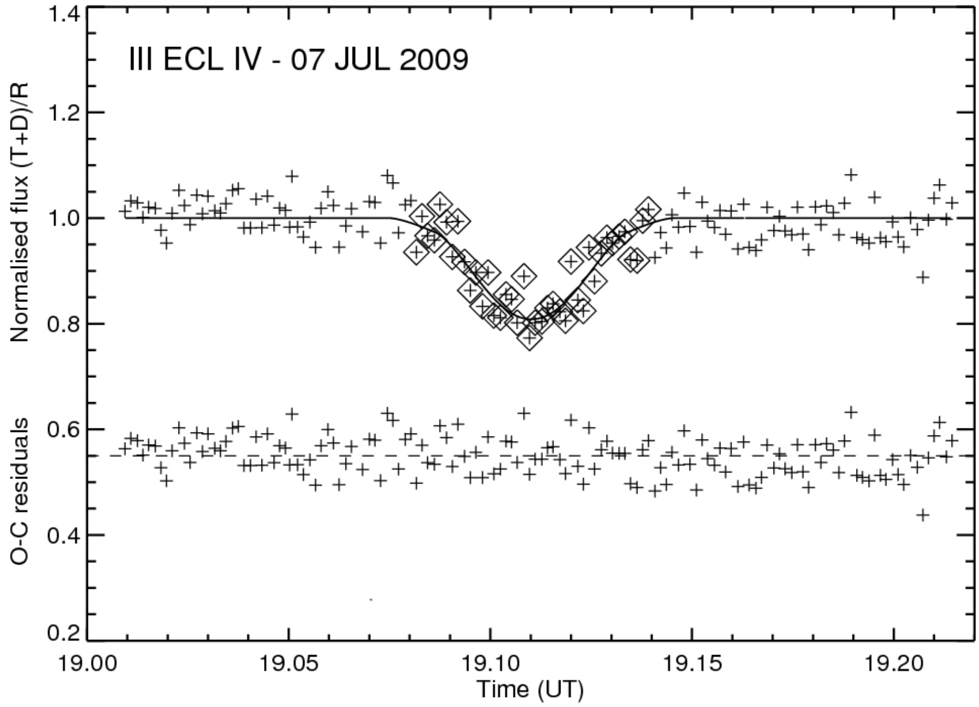

Figure 6: Best-fit model (continuous line) for the event 3E4P vs. observations (+ signs). The diamonds (◊ signs) indicate the observations, which were used for the fit. The + signs below and above the dashed line indicate the residuals after the fit.

DATE OF MINIMUM YYYY/MM/DD	EVENT	TIME OF MINIMUM (UT)		FLUX DROP (V-band)		IMPACT PARAMETER (KM)	
		TASS	D93	TASS	D93	TASS	D93
2008/12/19	4OCC5P	02:11:10	02:11:44	0.271	0.311	530	278
2008/12/24	3OCC2P	02:00:47	02:00:57	0.130	0.063	483	583
2009/07/07	3ECL4P	19:06:29	19:06:46	0.869	0.535	298	318

Table 5: The predictions of TASS και D93 for the time of minimum (UTC), the light flux drop in the V-band and the impact parameter for the three events. The value for light flux drop is given for the V-band.

EVENT	TIME OF MINIMUM (UT)	FLUX DROP	IMPACT PARAMETER (KM)
4 OCC 5 P	02:11:08±13sec	0.28 (I-band)	430±400
3 OCC 2 P	02:00:55±04sec	0.16 (I-band)	455±200
3 ECL 4 P	19:06:35.6±03sec	0.19 (V-band)	420±80

Table 6: The result of the observation of the three events. The observed flux drop is measured in the I-band for the first two events and in the V-band for the third event. The impact parameter is given in kilometers.

B7. Conclusions

In the case of the event 4O5P the time of minimum is in a better agreement with the TASS prediction, while in the case of 3O2P there is agreement with both predictions, given that the 4 second error (12 seconds at the 3-sigma level) is comparable to the time difference between the predicted times of the two models (12 seconds). As for the value of the impact parameter, there is a fairly better agreement with the TASS prediction, for both events. For the event 3E4P, the estimated mid-eclipse time is slightly better in agreement with TASS, but the two models predict essentially the same impact parameter, smaller than what we observe. Note that the measured flux drop is much lower than predicted. This is due to the fact that the photometric aperture also contained the satellite Tethys due to its proximity to Dione.

Our general conclusion is that the more recent TASS Ephemeris represents the differential positions of the satellites of Saturn with a better accuracy than the D93 Ephemeris. We hope that the comparison of these two 2008 events, as well as of others to follow in 2009, with the past events of 1980 and 1995 will more precisely define limits to values of tidal acceleration of the Saturnian satellites, mainly of the inner quartet Mimas, Enceladus, Tethys and Dione.

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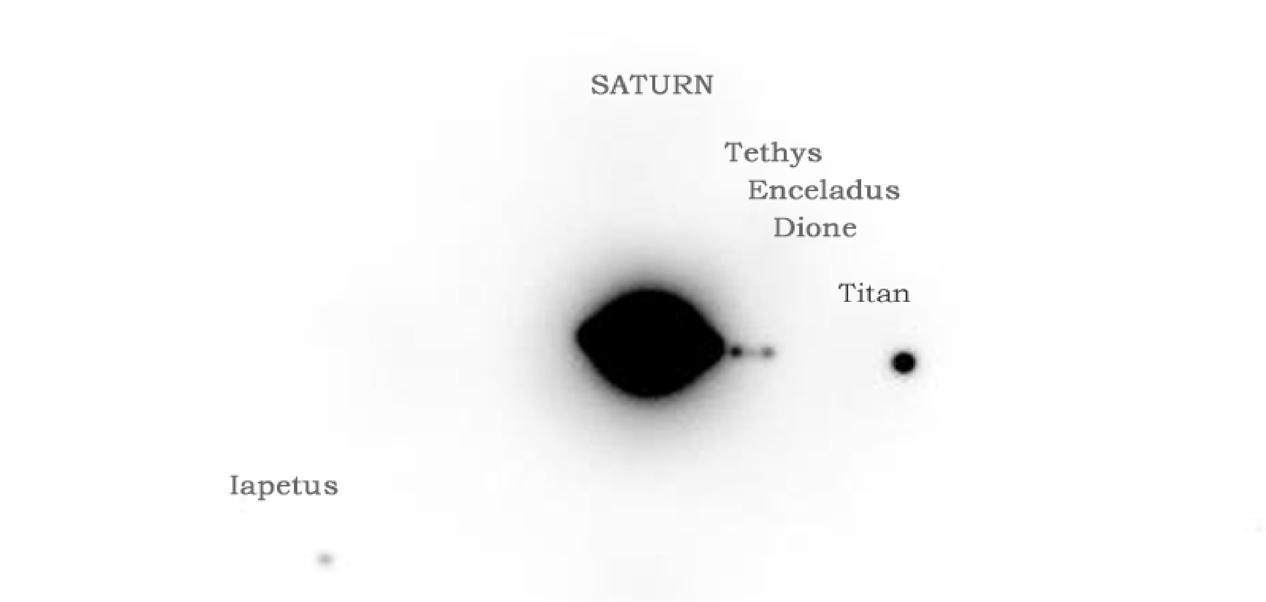
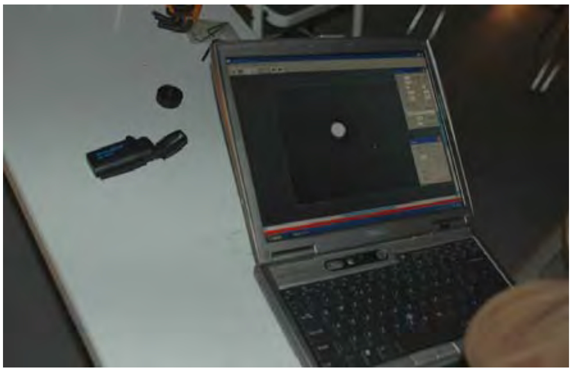
Appendix: Pictorial account of the observations



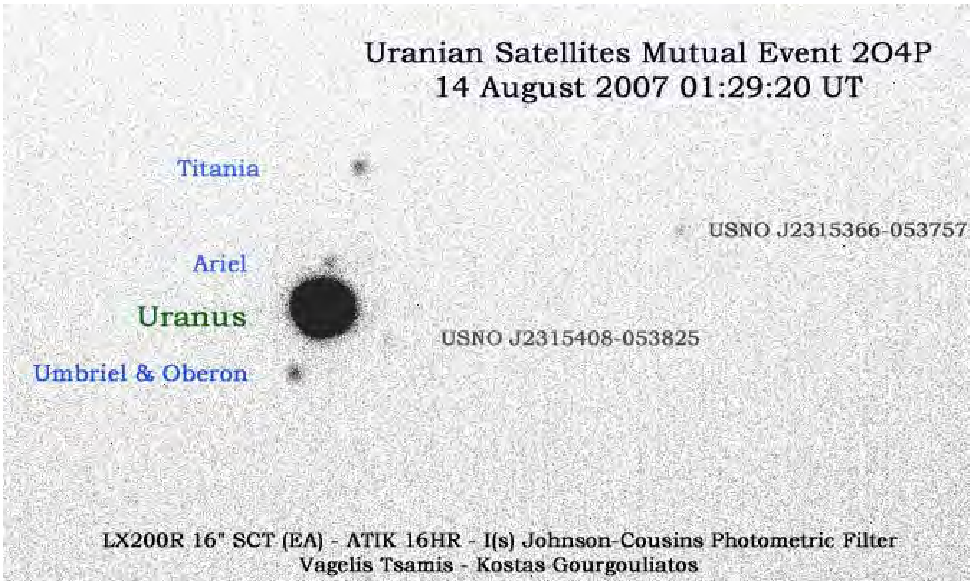
Saturn and five of its satellites, 40 minutes before the observation of the event 3O2P (24 Dec 2008)



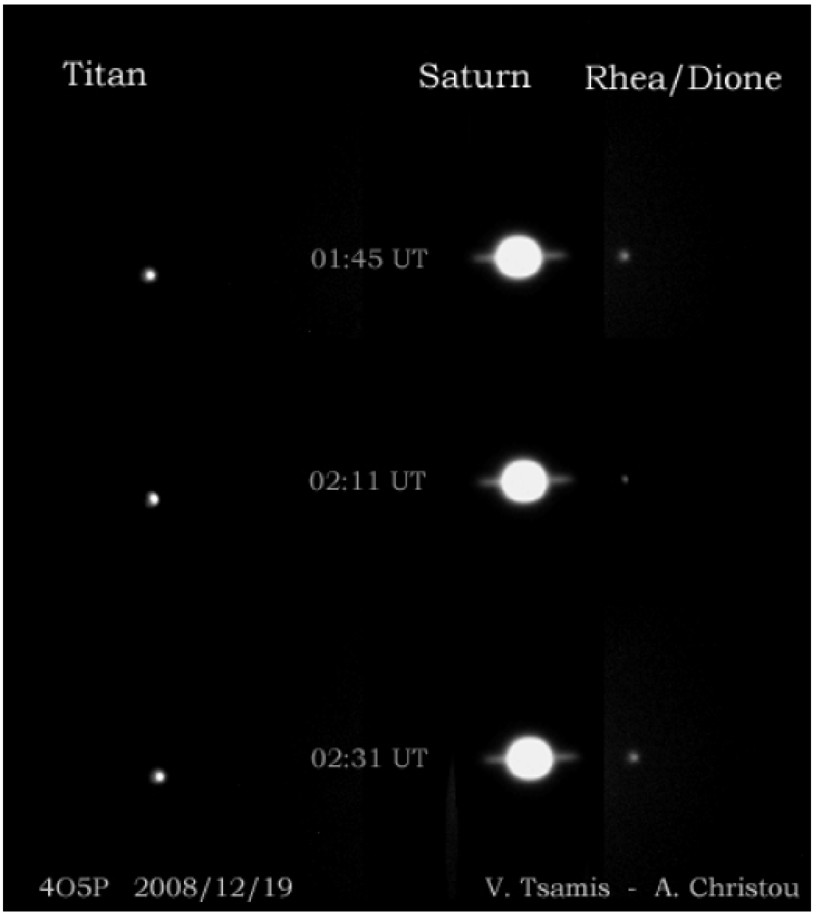
Imaging with Artemis Capture software

The 40 cm LX-200R telescope and the CCD ATIK-16HR

Ellinogermaniki Agogi School Observatory



First CCD observation of an Uranian mutual event in Greece



Saturnian mutual event 4O5P, December 19th 2008