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"CCD Photometry and Video Recordings of Uranian, Saturnian and Jovian Mutual Events in 2007, 2008 and 2009 – Measuring the loss of light in Athens and Sparta"

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Abstract
We present a set of observations of mutual events between satellites of the outer planets collected during the period 2007-2009 from several locations within Greece. Following a successful detection of a mutual occultation between the Uranian satellites Oberon and Umbriel in 2007 using a 16" instrument (Christou et al, A&A 2009) we observed, and reduced, two mutual events between Saturnian satellites in late 2008. Since May 2009, we have recorded several mutual eclipses and occultations between the Galilean satellites of Jupiter. We are planning to observe a number of additional Jovian and Saturnian events throughout the rest of 2009 and into 2010.

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.

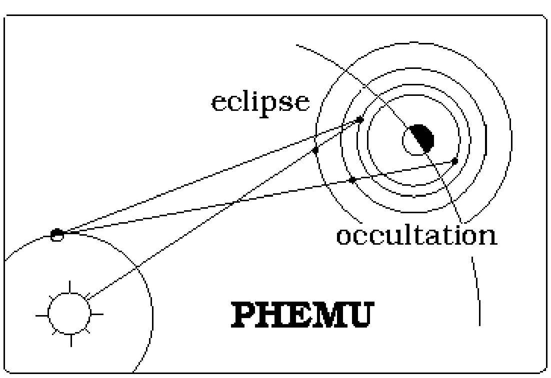


Figure 1: Geometry of the mutual events. Source: PHEMU Tech. Note #1, IMCCE, France

The Mutual Events - IMCCE

In 2008-2010, a series of eclipses and occultations will be occurring among the satellites of Jupiter and Saturn thanks to the equinox on these planets occurring in 2009 (figure 1). In 2006-2010 a same series of astronomical events is taking place between the satellites of planet Uranus. The observation of these events provides valuable data to the astronomical scientific community. 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). 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. For the Year 2009, IMMCE is organizing the campaigns PHESAT09 for Saturnian (Arlot & Thuillot 2009) and PHEMU09 for Jovian satellites.
(See: http://www.imcce.fr/page.php?nav=en/observateur/campagnes_obs/index.php).
The dates of oppositions, conjunctions with the Sun and equinoxes of Jupiter and Saturn for the year 2009 are presented in table 1.

	Jupiter	Saturn
opposition	August 14	March 9
conjunction with the Sun	January 24	September 18
transit of the Sun in the equatorial plane of the planet (equinox)	June 22	August 12
transit of the Earth in the equatorial plane of the planet (disappearance of the rings)	April 15	September 4
declination of the planet	-20 to -13 deg.	0 to 8 deg.

Table 1: Dates of oppositions, conjunctions with the Sun and equinoxes of 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 event 2O4P (2007)

On August 14th 2007 we carried out a successful observation of Uranian mutual event 2O4P, in which Umbriel partially occulted Oberon. This observation was part of a series of observations organized by Apostolos Christou during the planet's Equinox in 2007. Five different instruments have 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.

A1. Method & Equipment

The observation of the event 2O4P was carried out at Ellinogermaniki Agogi Observatory (ATH1) with a 40 cm f/10 telescope. For CCD imaging we used an ATIC 16-HR camera, set at no-binning mode. 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 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. Seeing at the time of observation was 4.35 arcsec.

A2. Results.

The light curve was model-fitted (figure 2) 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 tables 2 & 3)

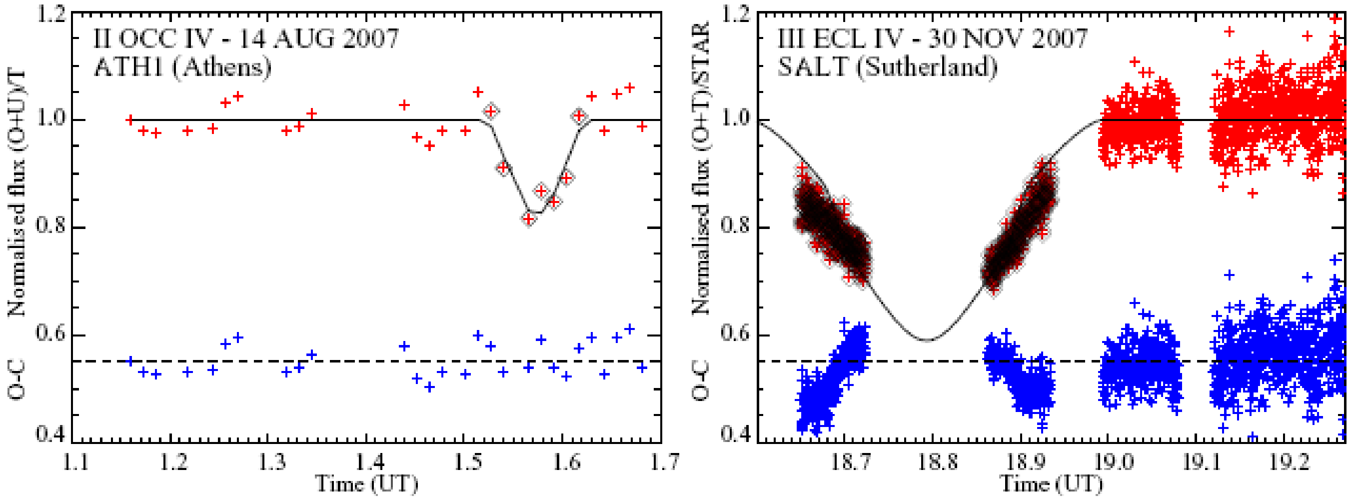


Figure 2: Model fit to observations acquired from Athens (ATH1; left panel) and Sutherland (SALT; right panel) (Christou et al, A&A 2009)

Date (DDMMYY)	Event Type	Obs. Site	Midtime (UT)	Impact Parameter (km)	Albedo Ratio	Relative Speed on impact plane (km/s)	Mean RMS of fit
040507	4O2P	FTS	19:09:53 ± 3	400 ± 70	$1.229^{a} \pm 0.1$	7.078^{a}	0.031
050807	4O2P	FTN	13:53:49 ± 30	850 ± 30	$1.238^{a} \pm 0.1$	1.225^{a}	0.019
140807	2O4P	ATH1	01:34:25 ± 28	750 ± 160	$0.813^{a} \pm 0.1$	5.765^{a}	0.083
220807	2E5T	FTN	15:03:37 ± 5	0 ± 60	0.410 ± 0.025 (0.617)	3.647^{a}	0.039
240807	1O2P	FTN	12:24:04 ± 30	840 ± 30	$1.833^{a} \pm 0.1$	2.210^{a}	0.018
121007	4E5T	FTN	09:51:53 ± 2	410^{+150}_{-410}	$1.271^{+0.55}_{-0.28}$ (0.759)	5.179^{a}	0.042
301107	1E5T	FTN	08:53:58 ± 2	310^{+90}_{-130}	$0.830^{+0.22}_{-0.14}$ (1.216)	7.403^{a}	0.040
301107	3E4P	SALT	18:47:36 ± 5	260 ± 150	$1.113^{a} \pm 0.1$	1.992^{a}	0.032

[a] These parameters have been assumed and kept fixed during the fitting process.

Table 2: Best-fit estimates of the parameters of the mutual events successfully observed from all telescopes participating in the Uranian campaign. Ellinogermaniki Agogi Observatory telescope is referred to as ATH1 (Christou et al, A&A 2009)

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 3: 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)

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 theoretically visible events was 19 including events with sun elevation < 0 deg, which are practically impossible to observe (see table 4). We carefully examined these events and we finally selected 2 events for 2008: Event 4O5P - Occultation of Rhea by Dione on 19 Dec 08 and event 3O2P – Occultation of Enceladus by Tethys on 24 Dec 08. Next, we studied the satellite motion 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:

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
BIT	16 BIT
Computer Port	USB 1.1 Download time max. 15s
Cooling	Peltier cooling (25° below ambient temp.)
Preview funtion	Only approx. 1 second download time
Power supply	12V DC - 0.8A power consumption
Protective glass	Optical glass - BK-7

B2. Spectral Region

Our previous observation experience of imaging the mutual event 2O4P in planet Uranus in 2007 (Christou et al 2009) suggested that in order to minimize the glare from the bright planet we should make the observations in the near infrared part of the spectrum, so we used a standard Bessell photometric infrared I(s) filter in capturing the events.

DATE OF MAXIMUM (TT) YR MT DAY H M S	EVENT :	FLUX	DUR. S	DIST. TO IN RJ	IMPACT "	RIGHT ASC. OF THE PLANET H M S	DECLINATION DEG ' "	DISTANCE TO THE EARTH AU	HOUR ANGLE HR	AZIMUT OF THE PLANET DEG	ELEV. OF THE PLANET DEG	AZIMUT OF THE SUN DEG	ELEV. OF THE SUN 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 35.7	10.118414	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 59.2	10.196316	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 14.9	10.426234	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.)

Table 4: The list of all 19 Saturnian mutual events observable from Athens, Greece.
Source: http://www.imcce.fr/page.php?nav=en/observateur/campagnes_obs/phesat09/prog_interactif.php

B3. Timing of the Events

As it is very important to have an accurate time base in capturing the mutual events in order for the results to be valid and comparable with others, 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 in the near infrared part of the spectrum with a Bessell Johnson-Cousins I(s) photometric filter. For capturing we used the Artemis CCD software, which is available with the ATIK 16-HR camera. Binning 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 302P we acquired 51 frames of 6 sec exposure time between UT 01:57:12 and UT 02:04:42 (24 Dec 08).

Figure 3: 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).

B5. Image Processing with AIP4WIN V2

We processed the series of CCD captured frames with AIP4WIN V2 software. For each frame we calculated the light flux of the occulted pair of satellites (variable light source) in relation to a third satellite (comparison light source) by means of differential photometry (Figure 3). In both cases the comparison light source was satellite Titan. In the case of 3O2P in particular, we used satellite Dione as a check light source. 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 in particular, due to the close proximity of the target to planet Saturn and after a series of tests with try and error method, 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 valid results.

B6. Processing of photometric points with IDL software

We used Interactive Data Language (IDL) software for the model fitting of the observed light curves. Our target was to acquire the time of minimum t_{min} and the impact parameter b (see figure 4) 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 and D93, given in table 5. Figures 5 and 6 present the best-fit model vs. observations.

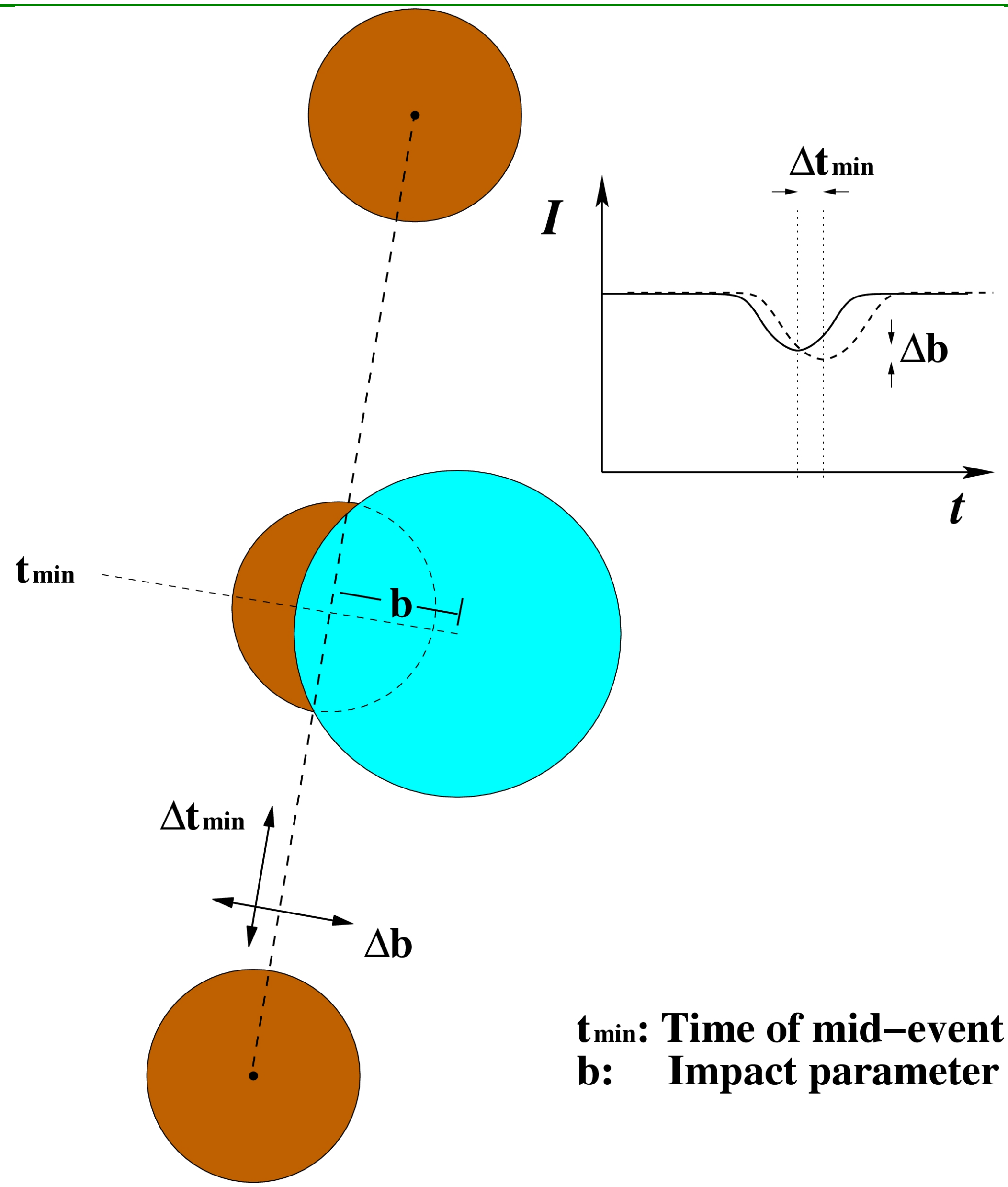


Figure 4: This diagram explains the geometry of the events. The blue disc of a satellite is occulting the brown disc of another satellite. The blue disc is larger than the brown satellite in this example, but it could be smaller. For each event there is an uncertainty Delta b in the impact parameter 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

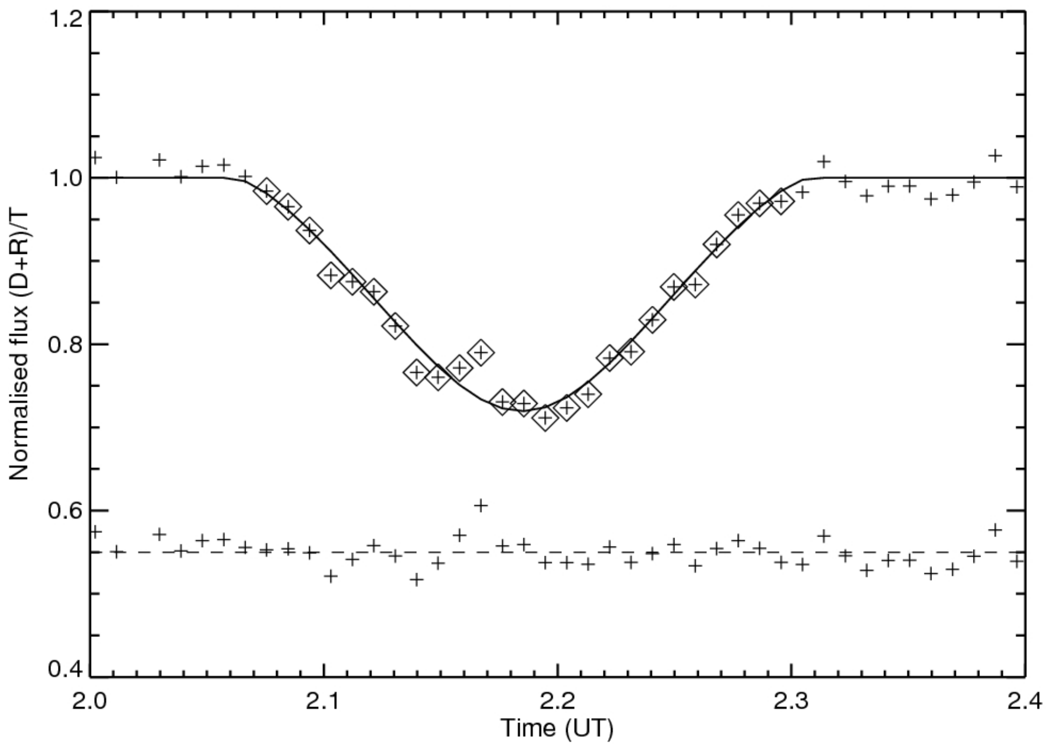


Figure 5: Best-fit model (continuous line) for the event 4O5P vs. observations (+ signs). The diamonds (◊ signs) indicate the observations, which were used for the fit. The + signs below and above the dashed line indicate the residuals after the fit.

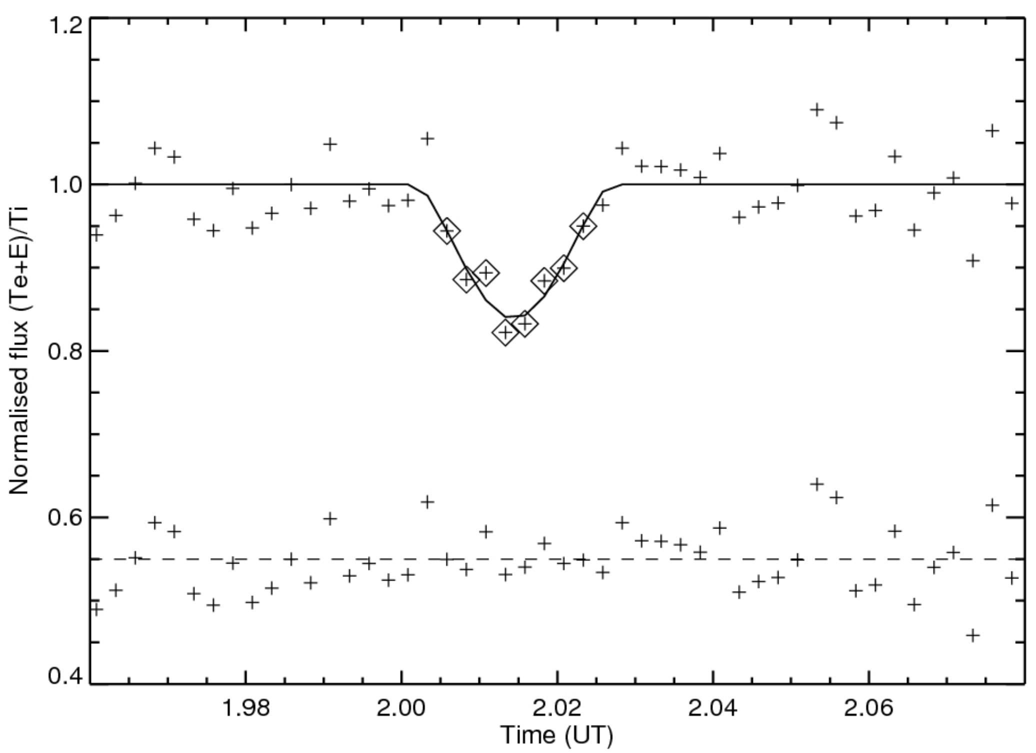


Figure 6: Best-fit model (continuous line) for the event 3O2P vs. observations (+ signs). The diamonds (◊ signs) indicate the observations, which were used for the fit. The + signs below and above the dashed line indicate the residuals after the fit.

DATE OF MINIMUM YYYY/MM/DD	EVENT	TIME OF MINIMUM (UT) TASS	TIME OF MINIMUM (UT) D93	FLUX DROP TASS	FLUX DROP D93	IMPACT PARAMETER (KM) TASS	IMPACT PARAMETER (KM) D93
2008/12/19	4OCC5P	02:11:10	02:11:44	0.271	0.311	530	281
2008/12/24	3OCC2P	02:00:47	02:00:57	0.130	0.063	483	583

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

EVENT	TIME OF MINIMUM (UT)	FLUX DROP (I-band)	IMPACT PARAMETER (KM)
4 OCC 5 P	02:11:08 +- 13sec	0.28	429 (1.0)
3 OCC 2 P	02:00:55 +- 04sec	0.16	403 (0.84)

Table 6: The result of the observation of the two events. The values in parentheses in the 3rd column show the albedo ratio values which were used for the calculation of the Impact Parameter b .

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 3-sigma region) 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.

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.

C. Observation of the Jovian mutual events (2009)

Teams consisted of members of "Sparta Amateur Astronomy Society – The Gemini" SAAS (www.spartastronomy.gr), a newly founded club in Greece, observed the Jovian mutual events. We are all very excited about this kind of observation and we are planning to observe as many mutual events in the future as possible. We are privileged to have our main observing site next to a mountain shelter at 1.420 m altitude, on top of Mt Parnon, in Peloponnesos, southern Greece, under one of the darkest skies available in Greece. At some cases SAAS members observed Jovian mutual events at Lavrion and Sounion regions, south of Athens city.

C1. Equipment

The equipment used is as follows:

a. Vagelis Tsamis & Kyriaki Tigani:
Telescopes: Meade LX-50 10” f/10 SCT & Meade ETX-125 5” f/15 MCT
CCD: ATIK 16-HR
Photometric Filter: Schuller – Astrodon I(s) infrared filter
CCD Video camera: WATEC 902-H2 Ultimate
Video Time Inserter: Tim-10 (Alexander Meier Elektronik)

b. Panagiotis Nikolakakos & Athanasios Douvris:
Telescopes: GSO 8” f/4 Newtonian Reflector & Skywatcher ED 80 Aperture 80mm f/7.5 Refractor
Mount: Skywather HEQ6 Pro
CCD: SBIG ST-4
Photometric Filter: Schuller – Astrodon V filter
CCD Video camera: WATEC 902-H2 Supreme
Video Time Inserter: Tim-10 (Alexander Meier Elektronik)

c. Yannis Effremidis:
Telescope: Vixen VMC 200L 8” f/10 KCT
Mount: Skywather HEQ5 Pro
CCD Video camera: WATEC 902-H2 Ultimate
Video Time Inserter: Tim-10 (Alexander Meier Elektronik)
Photometric Filter: Unfiltered

d. Antonis Farmakopoulos:
Telescopes: Celestron 9 1/4” f/10 SCT & Skywatcher ED 80 Aperture 80mm f/7.5 Refractor & Vixen R200SS 8” f/4 Newtonian Reflector
Mount: Skywather HEQ6 Pro
CCD: ATIK 16
Photometric Filter: Unfiltered

C2. Spectral Region

In most cases we used standard Bessel photometric filters in capturing the events: a Schuller - Astrodon I(s) infrared filter in order to minimize the glare from the bright planet Jupiter and a V (visual) filter. In some cases we used a Red photometric filter and in a few cases no filter was used.

C3. Timing of the Events

For CCD capturing, we used an Oregon Scientific RMB 899P DCF77 radio clock in order to synchronize our laptop clocks. For video recording of events we used Tim-10 Video Time Inserter devices.

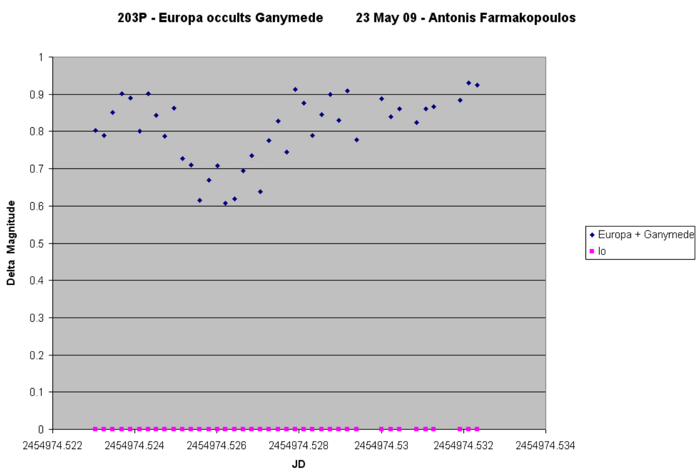
C4. Visual observations of Jovian mutual events

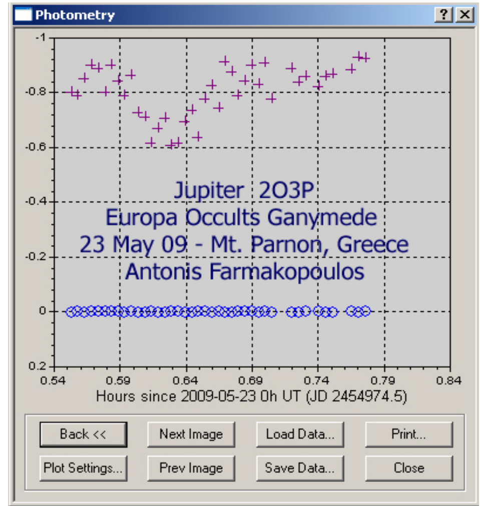
As a consequence of successful CCD observations of the Jovian mutual events in Greece, a growing interest for visual observation of these events was aroused in the national amateur astronomy community. Information about the mutual events was spread through Internet astronomy forums and a number of amateur astronomers throughout the country were motivated to make visual observations. Many observers describe this kind of observations as “witnessing a cosmic geometry lesson”.

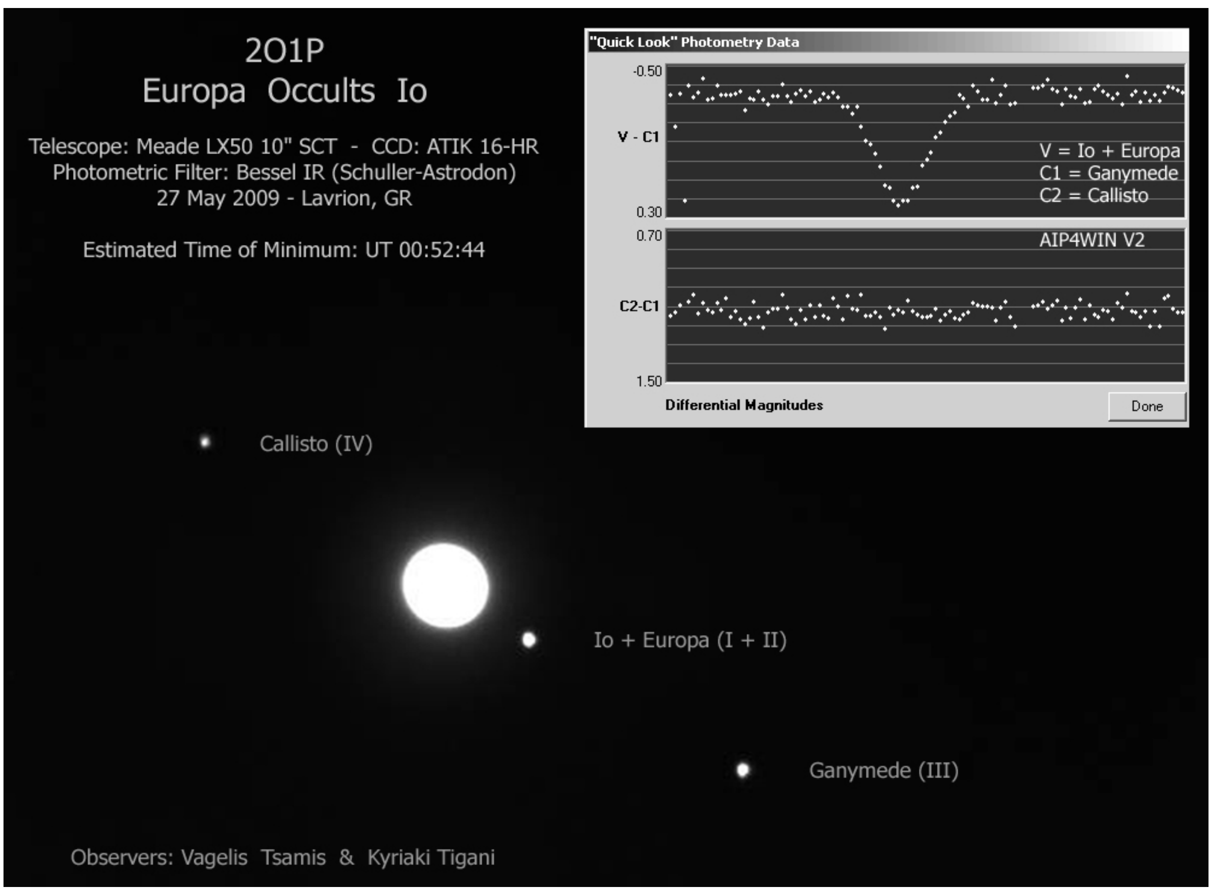
Quote from a post by amateur astronomer Dimitris Kapetanakis in www.astrovox.gr, describing a visual observation of the total eclipse of Europa by Ganymede on August 8th 2009: “The overall image was 3-

dimensional… It is a great feeling to realize that Celestial Mechanics is happening before your eyes… I noticed something unexpected: I focused on Europe, just next to Ganymede, and I detected a very faint, but clear and beautiful bluish color! At first I thought that this was just a misconception, but then I had the pleasure to confirm the color many times. The pleasure was unspeakable!"

C5. First Results







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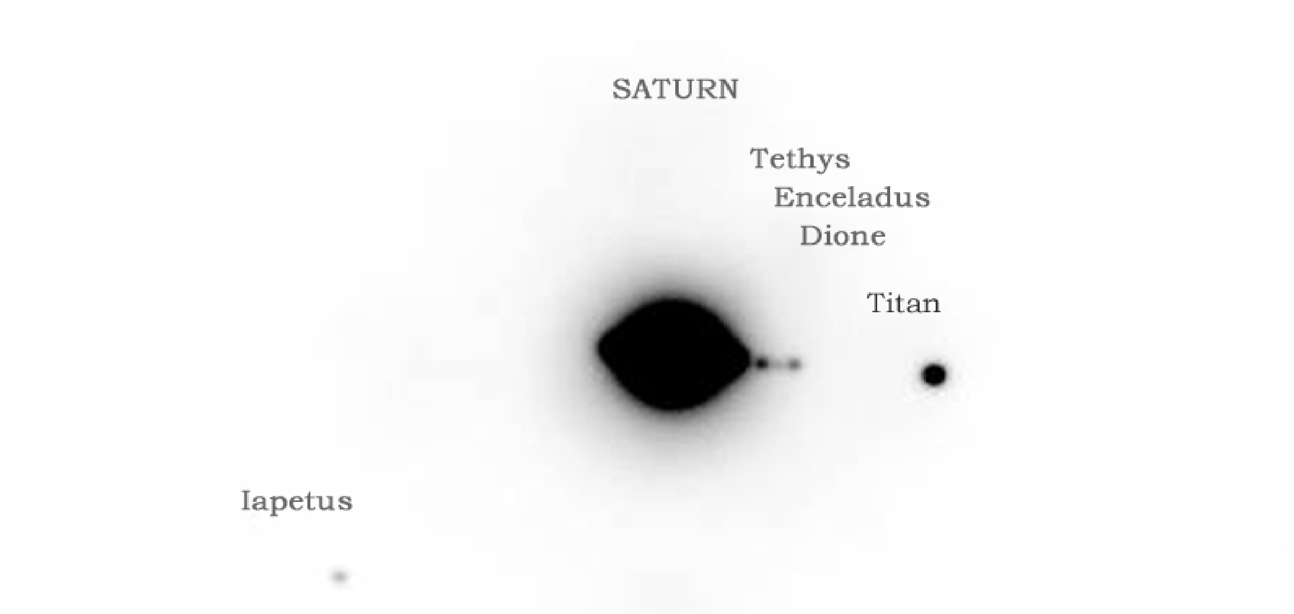
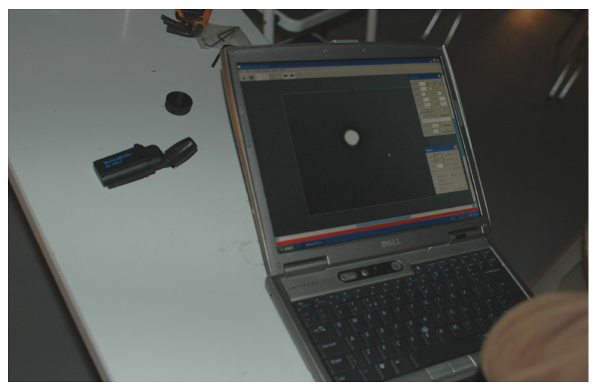
Appendix: Photo report of the observations



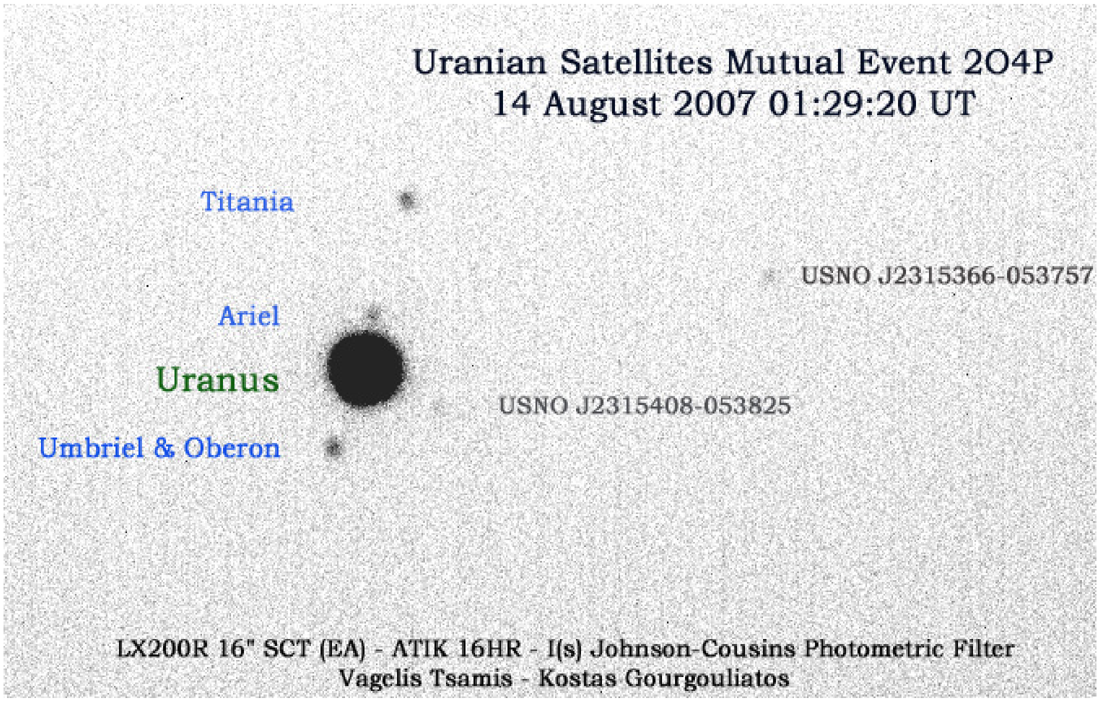
Saturn and five of its satellites, 40 minutes before the observation of the event 3O2P (24 Dec 2008)

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

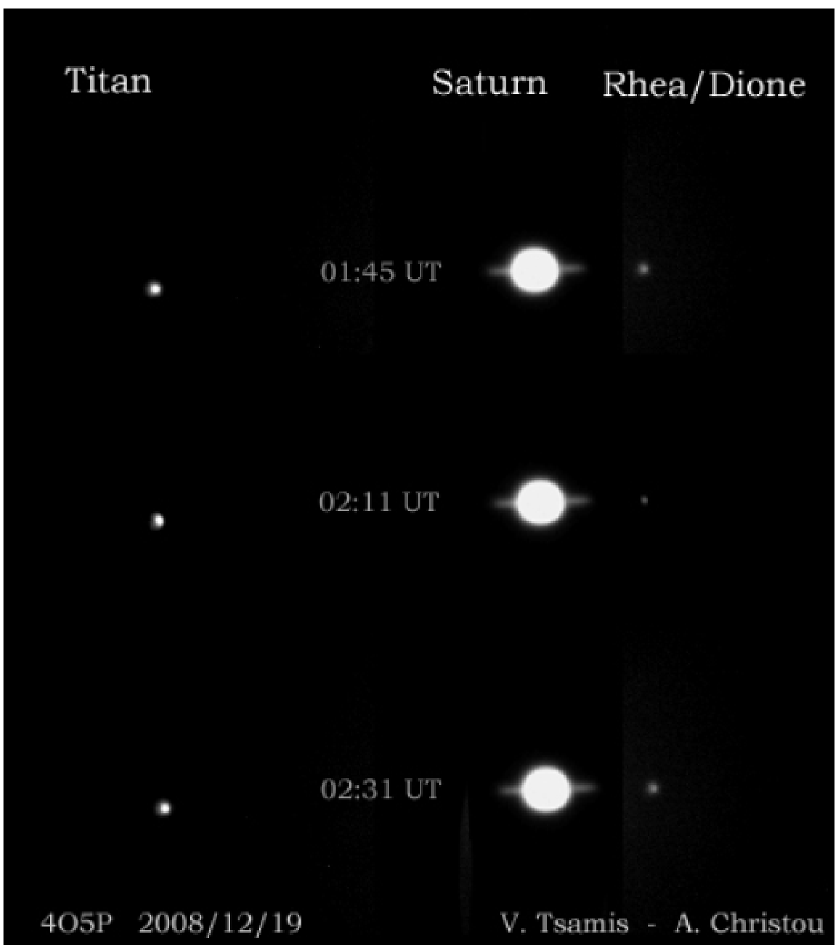


Imaging with Artemis Capture software

Ellinogermaniki Agogi School Observatory



First CCD observation of an Uranian mutual event in Greece



Saturnian mutual event 4O5P, December 19th 2009