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CCD observations of mutual events of Jovian satellites from VBO during 1997

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Abstract. CCD observations of the mutual events of the Galilean satellites of Jupiter from the Vainu Bappu Observatory during 1997 are presented. The derived times of close approach of the geometric centers of the satellites (satellite & shadow center) for the mutual occultations (mutual eclipses) are compared with the predictions. The residuals in observed times can be directly used to derive the relative longitude corrections of the two satellites involved in the mutual event. In the present data set, the (O-C) in longitudes of the 3O2 and 3E2 events indicate a delay in longitude of Europa or Ganymede by ≈ 190 km.

1. Introduction

As seen from the inner solar system, the Galilean satellite system appears edge on twice during the orbital period of ~ 11.6 years. This happens when Jupiter transits the nodes of its equatorial plane on its orbit. For about a few months around the time of crossing, the Galilean satellites occult and eclipse each other. The former events occur when the two satellites are aligned with the Earth and the latter when these are aligned with the Sun. Even in the post Galileo space probe era, observations of these events are important for obtaining astrometric information of the satellites to accuracies of the order of 0.03 arcsec corresponding to ≈ 100 km at Jupiter's distance. Data of this accuracy stretching to a period of 2-3 decades will be ideal to look for secular changes in the mean motion of the Galilean satellites, the inner three of which are locked into resonance. Such studies are important to investigate the tidal interactions between Jupiter and the innermost satellite Io. We present here, the preliminary results of the observations of the mutual events from the Vainu Bappu Observatory (VBO, 78°49′.58 E, 12°34′.58 N, 725 m) during 1997.

2. Observation and Reduction techniques

The observations were carried out at the cassegrain focus of the 102 cm Carl Zeiss reflector (CZ) and at the prime focus of the 234 cm Vainu Bappu Telescope (VBT). A photometric CCD with a liquid nitrogen cooled Thompson chip of 384 x 576 pixels was used at the 102 cm telescope. At the VBT, a photometric system with a liquid nitrogen cooled Tek1024 chip was used as the detector. To enable fast grabbing of the data, only a small portion of the chip was read. Region of CCD close to the starting edge of the arrays and columns was used to expedite the reading process. The sampling time for these events were mainly governed by the size of the data acquisition window which accommodated the two eclipsing satellites and a third satellite if available, for the occultation events, to enable differential flux measurements. The commands to start the exposures had to be given manually with the system at 102 cm telescope, the sampling time was therefore in the range of 7 - 15 sec. At the VBT, a macro written by Anbazhagan, Ravi and Rao (2001) permitted automated capturing of data with the PC based data acquisition system, from a pre-selected window. This permitted a shorter sampling interval in the range 4 - 9 sec. The PC at the VBT was synchronized to a GPS clock, the timings of data points from this telescope are therefore known precisely. On the other hand, as the clock of the data acquisition system at the 102 cm telescope had to be set manually, the sampling mid times of the data points have accuracies between ± 0.3 and ± 0.5 sec. However, the main source of error in deriving the time of light minimum comes from the scatter in the data points in the light curve due to photometric noise and sky transparency variations. For the occultation events, the individual satellites were imaged before and/or after the event for estimating the satellite flux ratio.

The images were reduced with the standard methods using IRAF. The photometric information was extracted using aperture photometry package of DAOPHOT. The two dimensional detector facilitated accurate determination of the sky background due to Jupiter. The optimal aperture size for flux extraction was determined for each event depending on the inter satellite separation and the extent of scattered light from Jupiter. Although several events were recorded, only those which had a reference satellite in the frame were found to be usable. Details of the observations and the event geometry are given in Table 1. The time of light minimum T_l^{Obs} in column 3 was derived by fitting a polynomial to the deeper portion of the light curve. The main source of error in determining this time comes from the limited sampling points inherent with the CCD data. Details of telescope, filter, hour angle of the object at mid time are given in columns 4 - 6 respectively. The relative geocentric (heliocentric) velocity of the satellites for occultations (eclipses) in the sense satellite 1 – satellite 2 are given in column 7. For all the events, this motion was west wards. The solar phase angle and the orbital geocentric (heliocentric) longitudes ϕ_1 of the occulting (eclipsing) and ϕ_2 of the occulted (eclipsed) satellites are given in columns 8 – 10. Projected distance of the satellites from Jupiter is given in column 11. All the events with the exception of the 12 July event occurred beyond 4.8 Jupiter radii. The scattered background due to Jupiter was hence significantly less compared to the flux from the bright satellites. The main uncertainty in determination of the intensity drop during the event was therefore due to changes in sky transparency and photon noise. Neutral density filters were used along with the broad band filters to avoid saturation on some of the days when the sky transparency was good.

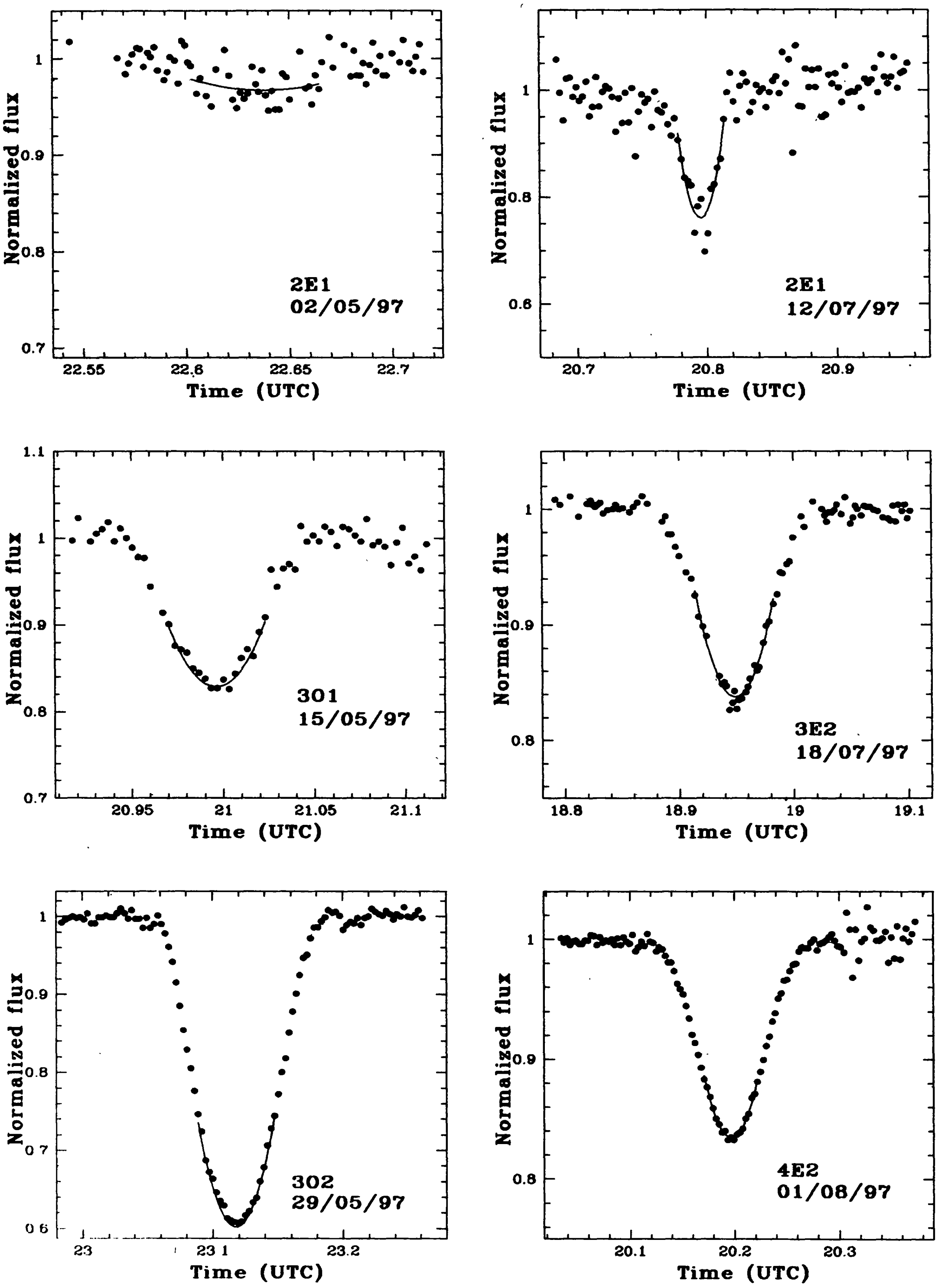

Figure 1. Observed light curves normalized with respect to flux from the eclipsed satellite (occulted + occulting satellites) for eclipses (occultations). The continuous line represents the fitted polynomial to evaluate the time of light minimum and intensity drop.

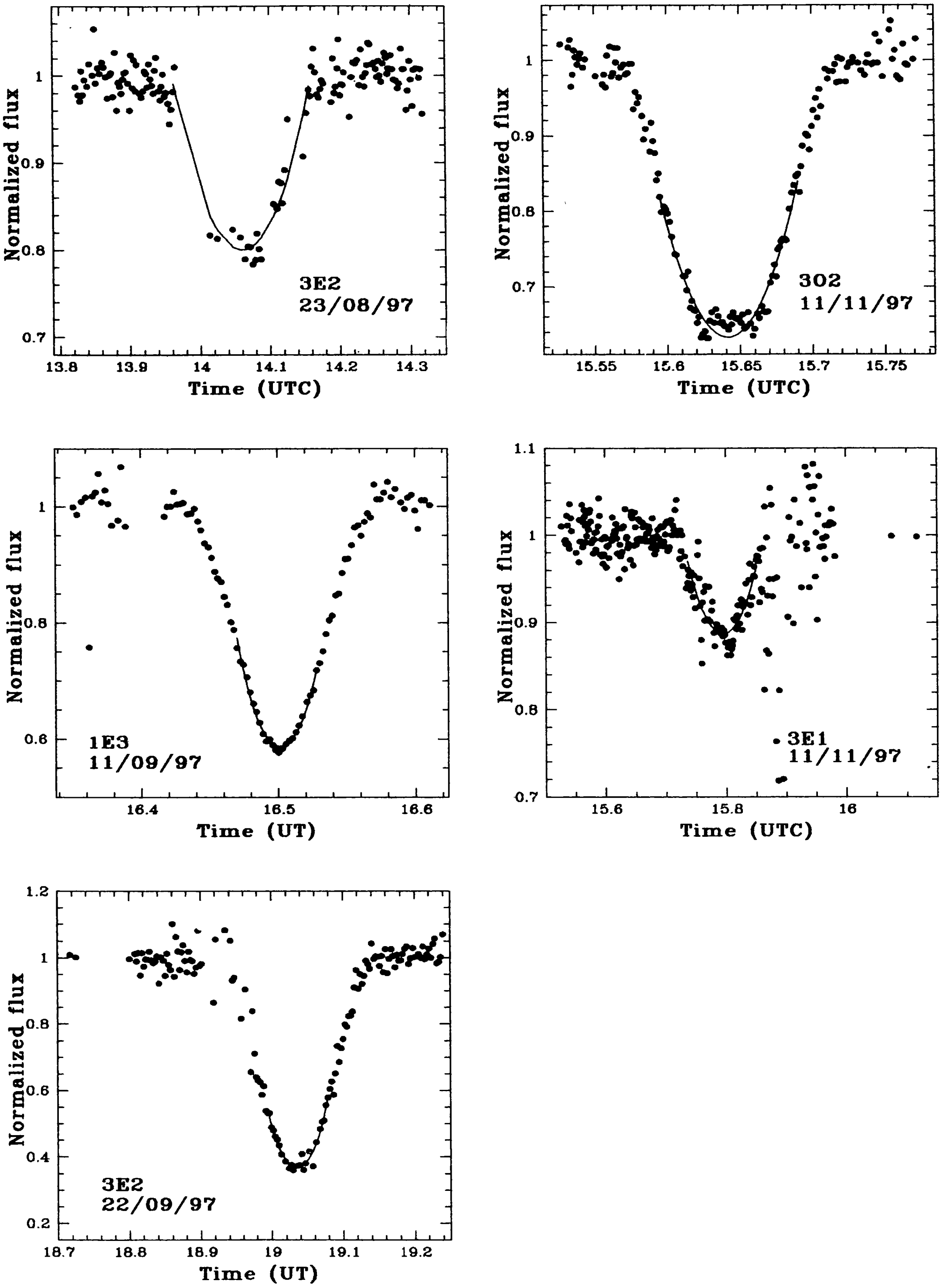

Figure 1. Continued.

2001BASI...29..511V

Table 1. Observations and predicted geometry

Date	Event	T_l^{Obs} UTC	Tel^1.	Filter^2	Hour Ang (hours)	Rel.vel. (km/s)	Phase (deg)	Orbital (deg)	long. (deg)	Dist. (R_J)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
02/05/97	2E1	22:38:17.4 ± 60s	CZ	R	– 2.849	– 24.67	– 11.3	206.2	315.5	4.9
15/05/97	3O1	20:59:45.8 ± 2.5	VBT	NB	– 2.812	– 20.30	– 11.4	161.3	54.8	4.8
29/05/97	3O2	23:07:03.8 ± 2.0	VBT	NB	– 0.734	– 17.47	– 11.0	149.5	53.6	7.6
12/07/97	2E1	20:47:42.0 ± 20.0	VBT	NB	– 0.078	– 30.17	– 05.7	190.9	342.4	2.3
18/07/97	3E2	18:56:54.9 ± 2.0	CZ	V	– 1.501	– 13.13	– 04.6	143.5	70.8	8.6
01/08/97	4E2	20:11:48.7 ± 1.0	VBT	NB	0.780	– 15.71	– 01.7	163.1	54.2	7.5
23/08/97	3E2	14:03:34.5 ± 15.0	CZ	V	– 3.838	– 06.90	03.0	141.5	96.1	9.2
11/09/97	1E3	16:30:04.3 ± 2.0	CZ	V	0.095	– 17.23	06.7	114.3	21.1	6.9
22/09/97	3E2	19:02:05.6 ± 3.5	CZ	O	3.401	– 10.20	08.4	218.5	277.6	9.0
11/11/97	3O2	15:38:28.1 ± 2.0	CZ	R	3.181	– 15.34	11.3	213.9	297.8	8.3
11/11/97	3E1	15:47:41.0 ± 2.0	CZ	R	3.343	– 11.32	11.3	203.0	274.2	5.6

1. Tel : VBT = 2.34 m Vainu Bappu telescope, CZ : 1.02 m Carl Zeiss telescope
2. Filter : NB = Narrow band filter 5141Å (118Å), O = No filter

3. Results and discussion

The time of light minimum T_l^{Obs}, corresponds to the time of close approach of the light center of the occulted (eclipsed) satellite to the geometric center of the occulting satellite (shadow center). As the theory predicts the time of close approach of the geometric centers of the satellites, T_l^{Obs} should first be subjected to phase correction to take into account the separation between the light center and the geometric center. The phase corrections to the observed time of light minimum corresponding to the event geometry were calculated following Aksnes, Franklin and Magnusson (1986) but assuming Lommel-Seeliger's law for limb darkening, as this was found to yield a better fit to the light curves compared to Lambert's law for the 1991

2001BASI...29..511V

Table 2. Relative astrometric positions at close approach and (*O–C*) in longitude

Date	Event	Phase	Correction	T_g^{Obs}	T_g^{Pred}	(*O–C*)	in Long.	Int.	Drop	Q[1]
		Time (sec)	Dist. (km)	UTC	UTC	Time (sec)	Dist. (km)	Obs.	Pred.	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
02/05/97	2E1	- 1.8	44	22:38:15.6 ± 60s	22:38:27.0	- 11.4 ± 60	281 ± 1480	0.033 ± 0.012	0.028	N
12/07/97	2E1	- 1.0	29	20:47:41.0 ± 20s	20:47:44.2	- 3.2 ± 20	97 ± 603	0.240 ± 0.036	0.297	N
15/05/97	3O1	4.6	- 93	20:59:50.4 ± 2.5s	21:00:06.5	- 16.1 ± 2.5	327 ± 51	0.172 ± 0.033	0.152	G
11/11/97	3E1	6.2	- 70	15:47:47.2 ± 20s	15:47:51.6	- 4.4 ± 20	50 ± 226	0.113 ± 0.021	0.181	N
29/05/97	3O2	5.9	- 104	23:07:09.7 ± 2.0s	23:06:58.8	10.9 ± 2.0	- 190 ± 35	0.398 ± 0.016	0.228	G
18/07/97	3E2	- 2.3	30	18:56:52.6 ± 2.0s	18:56:36.1	16.5 ± 2.0	- 217 ± 26	0.162 ± 0.008	0.240	F
23/08/97	3E2	2.6	- 18	14:03:37.1 ± 15.0s	14:03:31.9	5.2 ± 15	- 36 ± 104	0.200 ± 0.021	0.284	I
22/09/97	3E2	6.7	- 68	19:02:11.0 ± 3.5s	19:01:54.0	18.3 ± 3.5	- 187 ± 36	0.631 ± 0.033	0.673	F
11/11/97	3O2	- 6.8	105	15:38:21.3 ± 2.0s	15:38:10.5	10.8 ± 2.0	- 166 ± 31	0.367 ± 0.059	0.259	G
01/08/97	4E2	- 0.8	13	20:11:47.9 ± 1.0	20:11:29.6	18.3 ± 1.0	- 288 ± 16	0.166 ± 0.007	0.191	G
11/09/97	1E3	2.5	- 43	16:30:06.8 ± 2.0s	16:30:18.3	11.5 ± 2.0	198 ± 34	0.413 ± 0.021	0.422	G

Q : Quality of data, G = Good, F = Fair, N = Noisy, I = Incomplete light curve

series (Vasundhara, 1994). The derived times (T_g^{Obs}) of closest approach of the geometric center of the occulted (eclipsed) satellite from the geometric center of occulting satellite (shadow center) are given in column 5 of Table 2. The phase corrections in time and distance are given in columns 3 and 4 respectively. The sub Earth (sub Sun) point on the disc of occulted (eclipsed) satellite is to the West (East) of the light center before opposition and to the East (West) of the light center after opposition. Hence for a given direction of relative motion of the satellites and a given sign of the solar phase angle, the phase corrections for eclipses and occultations have opposite signs. The geometric mid times T_g^{Pred}, predicted by Arlot (1996) using G5 ephemerides are given in column 6. Columns 7 & 8 give the (*O–C*) in longitude in time and distance respectively, as derived from T_g^{Obs} and T_g^{Pred}. The observed and predicted intensity drops at mid event are given in columns 9 and 10 respectively. The intensity drop provides an estimate of the separation of two satellites at mid event along the latitude. The derived intensity drops in Table 2 are in general found to be higher for the occultations and lower for the eclipses compared to the predicted values. For the occultation events, as both the satellites are sampled in the aperture, the satellite flux ratio at the wavelength band of observation becomes important and will influence the magnitude drop. Hence, for comparison of the latitude separation, the impact parameter is a better measure than the intensity drop as the latter also depends on the limb darkening on the occulted/eclipsed satellite as well as the limb darkening on the sun at the wavelength band of observation in case of eclipses. Hence in absence of extraction of the impact parameter from the observed light curves, results in (*O – C*) in latitude are inconclusive in the present investigation. An index of the quality of the light curve is give in column 11. The quality is judged based on the noise and the data sampling rate. The former determines the accuracy of the magnitude drop which will affect the accuracy of the derived impact parameter. The latter is important for relative longitude corrections.

The (O – C) in latitude and longitude of a large number of events during several mutual event series are needed to update the constants of motions of the Galilean satellites (Lieske, 1998, Kaas et al., 1999, Vasundhara, Arlot and Descamps, 1996). Observations of mutual events are therefore made as part of International Campaigns (Arlot et al., 1992, 1997, 2001, Galilean Satellite Observers (GSO), 1991). In the present investigation, we analyze only a small sample of the 1997 series to look for (*O – C*) in longitude. From the preliminary results given in Table 2, it seen that the (*O–C*) in longitude of the 3O2 and 3E2 events indicate a delay in these types of events. This may either indicate a delay in longitude of Europa or that of Ganymede by ≈ 190 km (excluding the noisy event on 23 August). A similar delay in the 4E2 event which was recorded under good observing conditions favours the former. The delay may indicate need for up-gradation of the constants of motion of the satellites. This can be checked by detailed fits to the light curves using the recent ephemerides E5 by Lieske (1998). This ephemerides was generated by Lieske using astrometric positions of the satellites from CCD images, photographic plates, Voyager-mission optical navigation images, mutual event observations till 1991 and eclipse timings. Another equally important contribution to the delay in longitude may come from the displacement in the position of the light center with respect to the geometric centre due to albedo variations on the satellite. The present work only takes into account the displacement of the light centre from the geometric centre due to the effect of finite solar phase angle (Aksnes, Franklin and Magnusson, 1986) assuming a uniform disc model. Kaas et al. (1999) find that the residuals in right ascension of the satellites with respect to E5 for the 1991 mutual events have an average residual of -0.″05 (-150 km), while the residuals with respect to E3 (Lieske, 1987) were twice as large and were found to vary with orbital phase angle. They further report findings by J. Goguen (private communication with Kaas et al.) that an extensive bright region on Io would shift the satellites bright centre by about 130 km. Hence in the next phase of investigations, it is proposed to carry out a detailed fit using a model which includes albedo variation from

Voyager imagery and the E5 Ephemerides. As the recent mutual event series of 1997 have not been incorporated in the E5 ephemerides, the longitude residuals compared to E5 will be of particular interest.

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