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Mutual events between Galilean satellites observed with SARA 0.9 m and 0.6 m telescopes during 2014–2015

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ABSTRACT

Observation of mutual events has been confirmed to be a most effective and accurate ground-based method for obtaining accurate astrometric data by fitting the flux variation of involved satellites during the events, which is very invaluable for improving the orbital models of the natural satellites. The mutual events between the Galilean satellites occur every six years. During the observational campaign of 2014–2015, 21 mutual events between Galilean satellites were observed with the SARA 0.9 m and 0.6 m telescopes. The model proposed by Assafin et al. and Zhang et al. for mutual occultation and Zhang et al. for mutual eclipse were used to fit the light curves, taking the Lommel–Seeliger scattering law and the solar limb darkening into account. In this paper, the astrometric results of the Galilean satellites from the mutual events we observed will be shown, such as the impact parameter and its corresponding mid-time, and the velocity of occulting/eclipsing satellite relative to the occulted/eclipsed one.

Key words: techniques: photometric – eclipses – ephemerides – occultations.

1 INTRODUCTION

The planetary system likes a shrunk Solar system, to study its dynamics is most interesting and very invaluable for that of the Solar system. Thanks to the common orbital plane of natural satellites, the photometry of mutual events provides a most effective and accurate ground-based opportunity to obtain astrometric data of the natural satellites.

Mutual events can be observed on the Earth twice during one orbital period of planet, that is to say every six years for the Galilean satellites. Since 1973, the first observation (Aksnes & Franklin 1976), several observational campaigns of the mutual events between natural satellites had been performed, and the detailed history of all the past campaigns of mutual events between the natural satellites can be seen in Saquet et al. (2018) and its references. The most recent observation period of the mutual events between the Galilean satellites was during 2014–2015 (Vasundhara, Selvakumar & Anbazhagan 2017; Saquet et al. 2018).

In this paper, 21 light curves of mutual events between the Galilean satellites observed with the SARA 0.9 m and 0.6 m telescopes during 2014–2015 will be shown, along with the detailed descriptions of the observation, reduction, fitting, and the astrometric results of these mutual events.

2 OBSERVATION AND DATA REDUCTION

Our observations were carried out using the Southeastern Association for Research in Astronomy (hereafter SARA) 0.9 m telescope located at Kitt Peak National Observatory in Arizona (IAU code G82) and the SARA 0.6 m telescope at Cerro Tololo Observatory in La Serena (IAU code 807), from 2014 November 4 to 2015 April 9. Table 1 gives the specifications of both telescopes with attached CCDs. Table 2 shows the detailed information of our observations, J1, J2, J3, and J4 represent the Galilean satellites Io, Europa, Ganymede, and Callisto respectively. 'O' and 'E' are the abbreviations of occulting and eclipsing. 'SARA-KP' and 'SARA-CT' denote the SARA 0.9 m telescope located at Kitt Peak National Observatory and 0.6 m telescope at Cerro Tololo Observatory in La Serena, respectively.

Each image corresponds to one flux data of the two involved satellites relative to UT time, determined by their relative positions and surface properties. All images were maken bias and flat reduction before the flux of the involved satellites were calculated using the software of Image Reduction and Analysis Facility (IRAF; Tody 1986), with a Galilean satellite in the same field was used to be reference except the mutual events '20150211J2OJ1' and '20150211J2EJ1'. The flux variations of involved satellites before and after the mutual events were normalized to one.

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Table 1. Detailed information of the SARA 0.9 m and 0.6 m telescopes with attached CCDs.

Telescope	F-length	Field of view	Size of CCD
0.9 m	6858 mm	12.9 × 12.9 arcsec	2048 × 2048
0.6 m	5920 mm	14.7 × 14.7 arcsec	2048 × 2048

Table 2. Detailed observational information of mutual events with SARA telescopes.

UT Date	Event	Telescope	Filter	Exposure (s)
20141104	J2OJ3	SARA-CT	6975 H α	0.5
20141105	J1OJ3	SARA-KP	664/7	0.05
20141108	J3OJ1	SARA-KP	664/7	0.05
20141111	J2OJ3	SARA-KP	664/7	0.05
20141229	J3OJ1	SARA-KP	664/7	0.2
20141229	J3EJ4	SARA-KP	664/7	0.2
20150105	J3OJ1	SARA-KP	664/7	0.2
20150119	J3EJ1	SARA-KP	664/7	0.2
20150119	J3OJ1	SARA-KP	664/7	0.2
20150123	J4EJ3	SARA-CT	6975 H α	0.5
20150211	J2OJ1	SARA-KP	664/7	0.2
20150211	J2EJ1	SARA-KP	664/7	0.2
20150211	J4OJ3	SARA-KP	664/7	0.2
20150227	J4EJ3	SARA-KP	664/7	0.2
20150308	J2OJ1	SARA-KP	664/7	0.2
20150308	J2EJ1	SARA-KP	664/7	0.2
20150313	J1OJ3	SARA-KP	664/7	0.2
20150313	J1EJ3	SARA-KP	664/7	0.2
20150331	J3OJ2	SARA-KP	664/7	0.2
20150409	J2OJ1	SARA-KP	664/7	0.2
20150409	J2EJ1	SARA-KP	664/7	0.2

3 DYNAMIC AND PHOTOMETRIC MODELS

As introduced above, mutual events are caused by the relative positions of the Sun, satellites, and Earth (observer). Through establishing the photometric and dynamic models during a mutual event, the astrometric results of natural satellites can be inferred, such as the least distance between the two involved satellites 'impact parameter' along with its corresponding date 'mid-time', and the velocity of the occulting/eclipsing satellite relative to the occulted/eclipsing one. Considering the limb darkening of the Sun and the existence of penumbra zone for a mutual eclipse, different photometric model was adopted for a mutual eclipse from a mutual occultation.

3.1 Modelling a mutual occultation

For a mutual occultation, the photometric and dynamic model of Assafin et al. (2009) and Zhang, Arlot & Liu (2011) (Figs 1a and b) was adopted to fit the flux of the two involved satellites which has been normalized to one before and after mutual occultation, where discs S_1 and S_2 are assumed to be uniform, assuming that the occulted satellite was unmovable while the occulting one had a linear uniform motion relative to it.

The formula corresponding to the dynamic model for a mutual occultation we used is expressed as following:

$$F_{\rm occ} = \frac{F_{1o2}}{F_{1+2}} = 1 - \frac{R_1^2(\alpha_1 - \frac{1}{2}\sin 2\alpha_1) + R_2^2(\alpha_2 - \frac{1}{2}\sin 2\alpha_2)}{\frac{k_1}{k_2}\pi R_1^2 + \pi R_2^2} \quad (1)$$

$$\cos\alpha_i = \frac{R_i^2 - R_j^2 + d^2}{2R_i d} \quad (2)$$

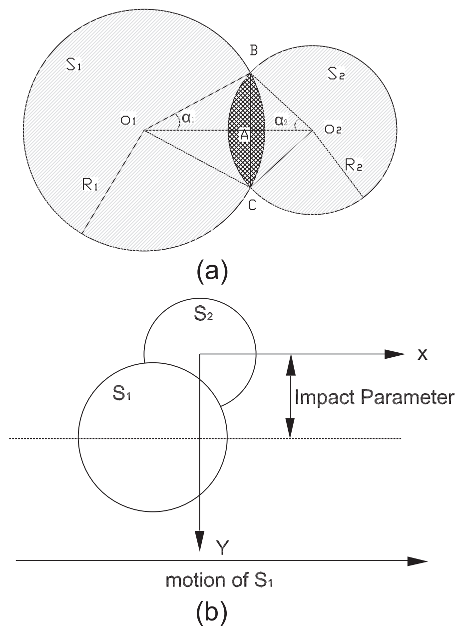

Figure 1. Geometry (a) and dynamical model (b) of a partial occultation where the discs S_1 and S_2 of radius $R_2 < R_1$ partially intercept each other with an area A, S_1, and S_2 representing the two satellites involved.

$$d^2 = d_0^2 + v^2(t - t_0)^2, \quad (3)$$

and i=1 or 2 and j = 2 or 1.

Where,

F_{1o2}, flux of involved satellites during mutual occultation.

F_{1+2}, flux of involved satellites before and after mutual occultation.

R_1, k_1 and R_2, k_2, radii and albedos of S_1 and S_2.

d, v, relative distance and velocity of occulting/eclipsing satellite to the occulted/eclipsed one.

d_0, t_0, impact parameter and its corresponding mid-time.

t, date of observation.

The Lommel–Seeliger scattering law (Surdej and Surdej 1978) was chosen to take the effects of phase angle and light scattering properties over the surface of satellites into account during analysing the mutual occultation.

3.2 Modelling a mutual eclipse

Different from a mutual occultation, the flux loss during a mutual eclipse is due to the decrease of the light reaching the eclipsed satellite. Fig. 2(a) shows the geometrical projection of the two involved satellites during a mutual eclipse of 'J1EJ2' as seen from the centre of the Sun (Zhang & Liu 2011), and Fig. 2(b) displays its dynamic model.

Hestroffer & Magnan's empirical law (1998) was adopted to model the light intensity in the penumbra zone, taking the Sun's limb darkening into account. And then following formula was finally used to calculate the flux loss of the eclipsed satellite:

$$F_{\rm loss} = \int_{A_{\rm U}}^{A_{\rm P}} (1 - i_\odot){\rm d}A + A_{\rm U} = \int_0^{A_{\rm P}} (1 - i_\odot){\rm d}A_{\rm P}. \quad (4)$$

$i_\odot$ represents the solar flux received by each point of eclipsed satellite in the penumbra zone, $A_{\rm P}$ and $A_{\rm u}$ are the parts of the

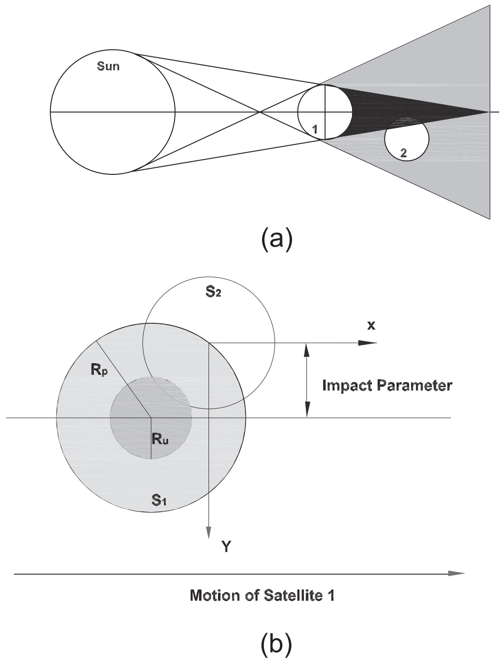

Figure 2. Geometry (a) and dynamical models (b) of a mutual eclipse 'J1EJ2', in which R_u and R_p are the radii of the umbra and penumbra zone, respectively.

eclipsed satellite's surface in the penumbra and umbra zones, respectively.

4 ANALYSIS AND RESULTS

Adopting the dynamic and photometric models introduced above, we fitted the 21 light curves of mutual events observed with the SARA telescopes and the results were shown in Table 3, in which the first to third columns denote the observed dates, types, and reference satellites, the observed mid-times is given in the fourth column, the fifth column is the albedo ratios of the occulting to occulted satellites for all mutual occultation and that of the eclipsing to eclipsed satellite for the mutual eclipse of 'J2EJ1' on 2015 February 11, the impact parameter, the relative velocity of occulting/eclipsing satellite to the occulted/eclipsed one, the observed and calculated maximum magnitude drops of involved satellites during mutual events with their errors together are given in the sixth to ninth columns, the last column displays the phase angles of involved satellites during observations.

The flux of involved satellites relative to another one in same field were calculated, except the mutual events of '20150211J2O1' and '20150211J2E1' because J3 and J4 were too close to the involved satellites J1 and J2 during the mutual events. The observed and fitted light curves, indicated by dots and bold line, respectively, are plotted in Fig. 3, with the flux of the satellites involved being normalized to one before and after the mutual events.

5 DISCUSSION

By comparison with the online ephemerides provided by IMCCE, we can find that the differences between the observed and calculated maximum magnitude drops are tiny for the mutual occultation however very large for some mutual eclipses such as the events of '20150123J4E3', '20150227J4E3', and '20150308J2E1', whose observed minus calculated values of maximum magnitude drops reach −0.632, −0.467, and 0.180, respectively, and are independent of the albedo ratios because only the flux of eclipsed satellites were measured during these mutual eclipses. For the mutual eclipse

Table 3. Astrometric results.

Date y m d	Type	Ref	Mid-time (UT) (h m s)	k_1/k_2	Impact (arcsec)	Relative velocity (mas s^{-1})	Δ(m) obs	 cal	Phase angle (°)
20141104	J2OJ3	J1	09 09 13.56 ± 1.15	9.96	0.1589 ± 0.0171	3.75 ± 0.02	0.271 ± 0.026	0.283	10.66
20141105	J1OJ3	J4	10 21 39.56 ± 0.03	16.95	0.2053 ± 0.0001	6.09 ± 0.26	0.125 ± 0.091	0.131	10.69
20141108	J3OJ1	J2	11 00 31.61 ± 0.04	0.21	0.5132 ± 0.0001	7.15 ± 0.01	0.303 ± 0.034	0.280	10.69
20141111	J2OJ3	J4	12 42 35.03 ± 1.89	1.68	0.2564 ± 0.0151	3.36 ± 0.04	0.294 ± 0.031	0.283	10.76
20141229	J3OJ1	J4	05 28 54.83 ± 1.74	0.68	0.5666 ± 0.0864	4.29 ± 0.15	0.375 ± 0.079	0.318	7.47
20141229	J3EJ4	J3	05 59 20.62 ± 2.92		1.0135 ± 0.0055	4.53 ± 0.13	0.179 ± 0.041	0.241	7.46
20150105	J3OJ1	J4	08 22 52.06 ± 2.17	0.31	0.5605 ± 0.0339	5.27 ± 0.10	0.266 ± 0.031	0.233	6.36
20150119	J3EJ1	J3	12 31 13.84 ± 3.10		0.9887 ± 0.0044	4.53 ± 0.21	0.099 ± 0.018	0.196	3.79
20150119	J3OJ1	J2	13 39 20.45 ± 2.25	1.01	0.4018 ± 0.0794	7.94 ± 0.19	0.182 ± 0.036	0.181	3.78
20150123	J4EJ3	J4	09 12 36.20 ± 0.78		1.0252 ± 0.0022	5.28 ± 0.04	0.761 ± 0.077	1.393	3.02
20150211	J2OJ1	N	11 00 33.59 ± 0.96	2.47	0.1459 ± 0.0801	4.81 ± 0.07	0.447 ± 0.031	0.424	1.00
20150211	J2EJ1	N	11 12 42.16 ± 0.37	0.17	0.5652 ± 0.0341	4.00 ± 0.06	0.405 ± 0.028	0.769	1.00
20150211	J4OJ3	J2	12 36 40.61 ± 2.54	4.31	0.4677 ± 0.0904	2.86 ± 0.03	0.176 ± 0.078	0.159	1.00
20150227	J4EJ3	J1	04 33 21.14 ± 1.41		1.0942 ± 0.0026	4.77 ± 0.07	0.114 ± 0.016	0.581	4.18
20150308	J2OJ1	J3	06 18 01.19 ± 0.59	1.79	0.1299 ± 0.0732	6.03 ± 0.07	0.589 ± 0.020	0.545	5.83
20150308	J2EJ1	J2	07 23 57.39 ± 0.13		0.3965 ± 0.0006	5.98 ± 0.01	0.953 ± 0.034	0.770	5.84
20150313	J1OJ3	J4	07 35 24.46 ± 1.07	5.99	0.2339 ± 0.0226	5.34 ± 0.05	0.321 ± 0.031	0.354	6.67
20150313	J1EJ3	J4	09 58 45.41 ± 0.71		0.5476 ± 0.0018	3.65 ± 0.02	0.705 ± 0.094	0.836	6.68
20150331	J3OJ2	J4	06 15 11.66 ± 0.02	0.61	0.8975 ± 0.0596	5.99 ± 0.77	0.044 ± 0.015	0.002	9.05
20150409	J2OJ1	J3	03 54 15.86 ± 0.63	2.97	0.5057 ± 0.0675	6.95 ± 0.35	0.169 ± 0.010	0.173	9.86
20150409	J2EJ1	J2	05 40 17.96 ± 3.74		0.9630 ± 0.0051	6.00 ± 0.66	0.036 ± 0.013	0.134	9.86

Note: k_1 and k_2 are albedos of occulting/eclipsing and occulted/eclipsed satellites. 'N' means no suitable reference satellite can be used. 'cal' represents the calculated maximum magnitude drop of the mutual events provided by Institut de mecanique celeste et de calcul des ephemerides (IMCCE), Observatoire de Paris.

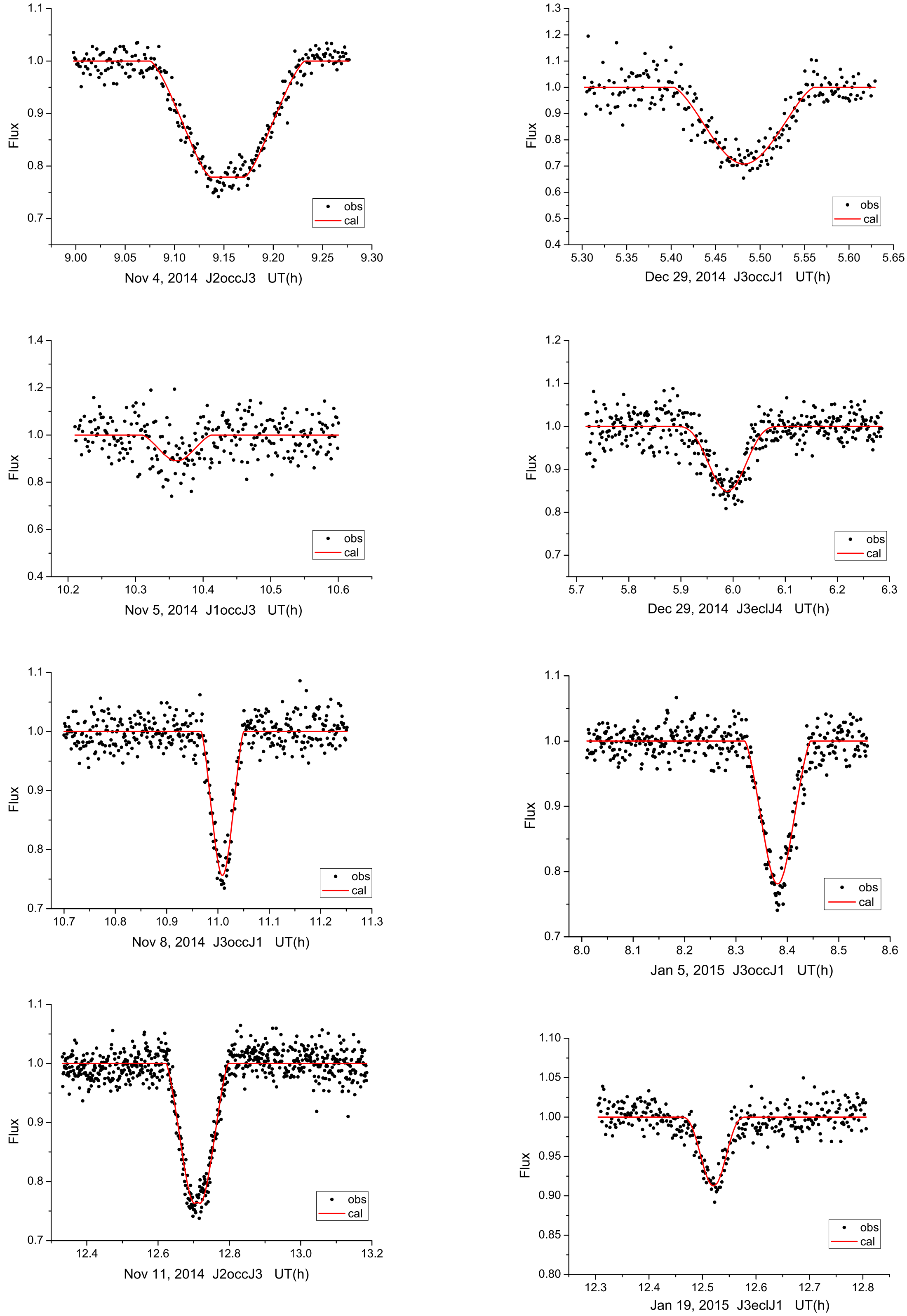

Figure 3. Observed and fitted light curves of involved satellites. The dots and bold lines represent the observed and fitted flux variations of involved satellites normalized to one before and after the event, respectively. The *x*-axis corresponds to the date (in hours) and the *y*-axis to the relative flux.

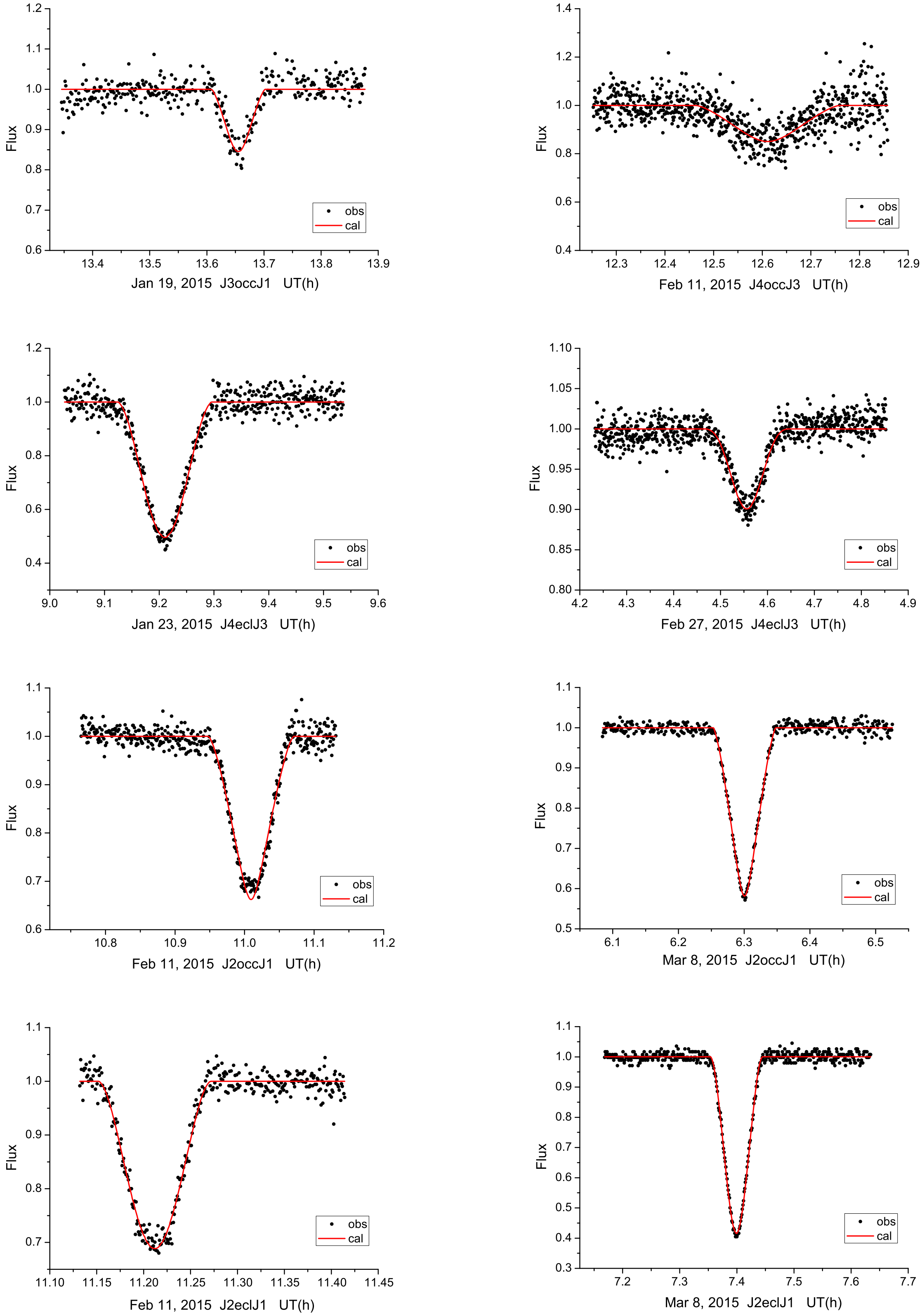

Figure 3. – *continued*

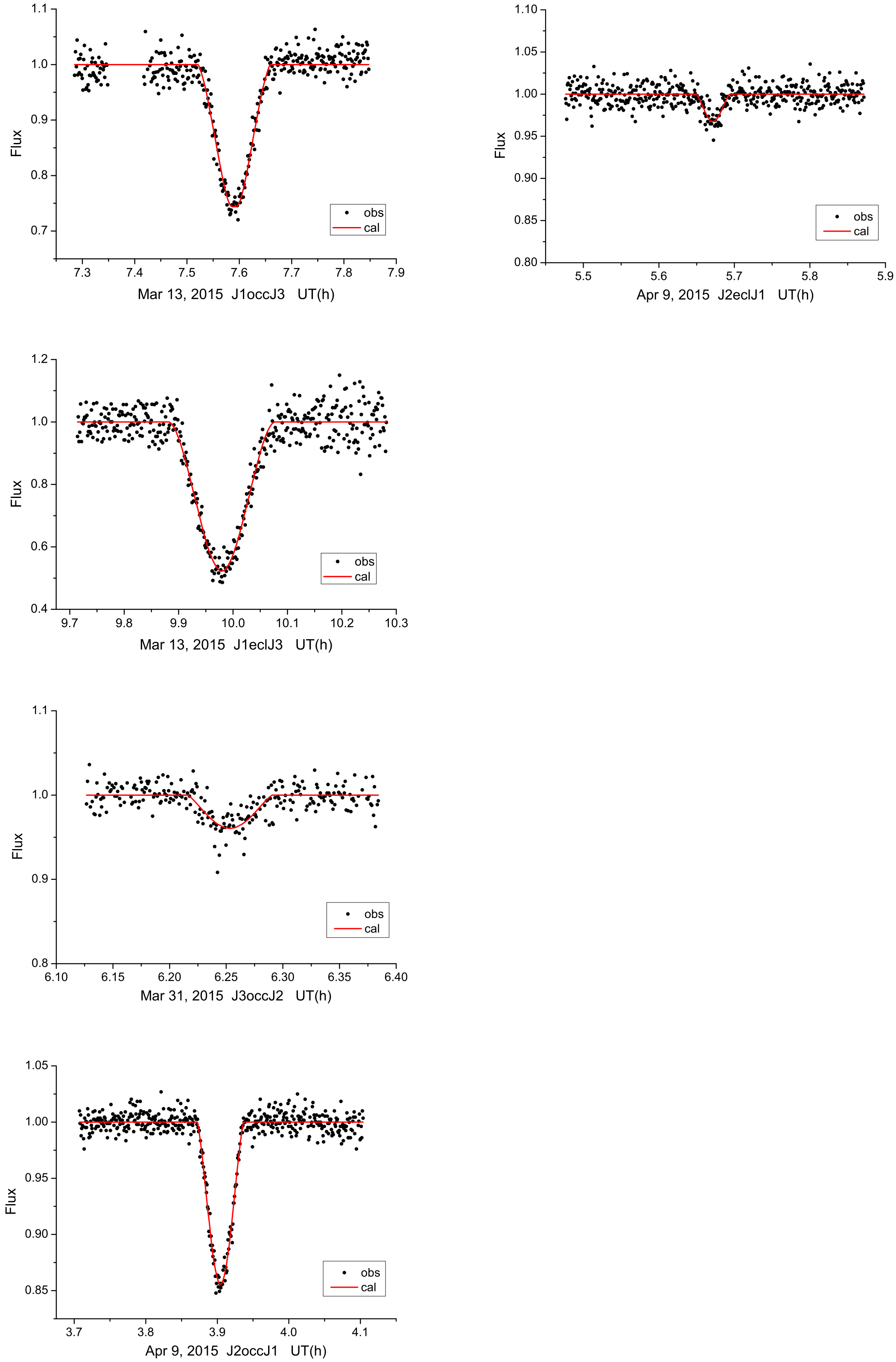

Figure 3. – *continued*

'20150123J4E3', its smaller observed maximum magnitude drop results from a bigger observed impact parameter. What's interesting is that, the observed maximum magnitude drops for the mutual eclipses '20150227J4E3' and '20150308J2E1' differ from the calculated values oppositely to the effect of the impact parameters, therefore more accurate data is necessary to determine if it is caused by the surface properties of the eclipsed satellite or the photometric model. For the annular occultation of '20141104J2OJ3' whose impact parameter $d_0 < r_{J3} - r_{J2}$, the bottom of its observed light curve shows a small fluctuate (shown in Fig. 3) caused by the non-uniform surface of the Galilean satellite J3. As we known, the flux variation during mutual events depends on the relative position, the surface shape and scattering properties of involved satellites, so more high accurate astrometric data are necessary to develop the theoretical model and learn about the photometric properties of the Galilean satellites.

Our results and photometric light curves will be added to others and helpful for determining small effects such as tidal ones in the dynamics and then developing the dynamical models of the satellites.

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