Research in Astron. Astrophys. **2011** Vol. **11** No. **10**, 1243–1248
*http://www.raa-journal.org* *http://www.iop.org/journals/raa*

*Research in Astronomy and Astrophysics*

# Mutual eclipses of J2 Europa by J1 Io observed at Yunnan Observatory in 2009

Xi-Liang Zhang[1,2] and Zhong Liu[1]

[1] National Astronomical Observatories / Yunnan Observatory, Joint Laboratory for Optical Astronomy, Chinese Academy of Sciences, Kunming 650011, China; *zhangxiliang@ynao.ac.cn*
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Received 2011 May 3; accepted 2011 May 29

**Abstract** Mutual events between natural satellites include mutual occultation and mutual eclipse. Mutual eclipse is another kind of mutual occultation as viewed from the center of the Sun instead of the Earth. Two mutual eclipses of J2 Europa by J1 Io (2009 Aug. 28 and Sept. 12) were observed at Yunnan Observatory during the PHEMU09 international campaign. We will calculate the astrometric data of these Galilean satellites by analyzing and fitting the light curves we obtained. The limb-darkening was considered during modeling the light intensity of eclipsed satellites in the penumbra zone, by taking the Lommel-Seeliger scattering law into account. Several dynamical quantities, such as the relative coordinates of the eclipsing satellite from the eclipsed one $\Delta\alpha\cos\delta$ and $\Delta\delta$, impact parameter and mid-time corresponding to the impact parameter and the deviations $O-C$ of observed $\Delta\alpha\cos\delta$ and $\Delta\delta$ relative to ephemerides, were obtained for each event respectively.

**Key words:** eclipses — kinematics and dynamics-methods — planets and satellites: individual: Galilean satellites

## 1 INTRODUCTION

Dynamics of Galilean satellites of Jupiter is one of the most interesting but difficult problems in the study of the Solar System because of the complicated effects at play. Therefore, accurate astrometric data of Galilean satellites are very necessary. Photometry of mutual events between natural satellites has been verified to be the most effective and accurate ground-based method to measure astrometric data of these natural satellites.

Mutual events, caused by the relative positions among the Sun, satellites and the Earth (observer), happen twice during one orbital period of Jupiter, that is to say every six years for the Galilean satellites. Since 1979 when the first worldwide campaign was organized, six international observation campaigns of the mutual events between Galilean satellites have been performed.

In 2009, two mutual eclipses between Galilean satellites, predicted by (2), were observed at Yunnan Observatory. The main idea of this paper is to give the light-curves we obtained and to calculate several dynamical quantities of two such events. Detailed explications of observations, reductions, analyzing and fitting of light curves and the astrometric results of such mutual eclipses will be given in the following sections.

## 2 CCD PHOTOMETRIC OBSERVATION

Our observations were carried out with a DW436 $2048 \times 2048$ CCD, attached to the 60-cm telescope at Yunnan Observatory ($102°47.3'$E, $25°1.5'$N, altitude=2000 m, IAU code 286), on 2009 Aug. 28 and Sept. 12. The effective field of view of the 60-cm telescope at the Cassegrain focus was about $12 \times 12$ square arc min. During the observations, Johnson's $R$ filter was used. There are three choices of CCD readout rates (50, 100 and 150 kHz); in order to obtain as many points as possible, we chose the fastest readout mode (150 kHz). Table 1 shows the specifications of the 60-cm telescope at Yunnan Observatory, with the attached CCD.

**Table 1** Specifications of 60-cm Telescope at Yunnan Observatory, with Attached CCD

| Telescope | F-length | CCD FOV | Size of Pixel | Size of CCD | Size/pixel |
|---|---|---|---|---|---|
| 60-cm | 7500 mm | $12' \times 12'$ | $13.5\,\mu m \times 13.5\,\mu m$ | $2048 \times 2048$ | $0.35''$ |

## 3 DATA REDUCTION

Before the flux of the involved satellites was calculated, each image was bias-corrected and flat-fielded, then the curves of flux variations relative to UT time were obtained for each event. In this paper, because the satellites J1 Io and J2 Europa were too close to separate during the eclipse, we measured the total flux of both of the involved satellites for the event of 20090828J1EJ2, and only the flux of the satellite J2 Europa was measured for the event of 20090912J1EJ2. The main goal of photometry of mutual events is to calculate the dynamical quantities of involved satellites through analyzing and fitting their flux variations during the events.

Table 2 shows the details of our observations and reductions, where J1, J2 and J3 are the Galilean satellites Io, Europa and Ganymede respectively, 'Flux' means the satellite(s) we measured and 'Ref' indicates the satellite used as a reference for the photometry. In this paper, J3 Ganymede is used as the reference for the event of 20090828J1EJ2 and J2 Europa for the event of 20090912J1EJ2. 'Telescope' shows the apertures of the used telescopes whose complete specifications are provided in Table 1; both observations used a Johnson $R$ filter and 'Exposure' gives the exposure time.

**Table 2** Observational Details of Mutual Eclipses J1EJ2 at Yunnan Observatory in 2009

| Date (y m d) | Flux | Ref | Telescope | Filter | Exposure (s) |
|---|---|---|---|---|---|
| 2009–08–28 | J1+J2 | J3 | 60-cm | $R$ | 0.2 |
| 2009–09–12 | J2 | J1 | 60-cm | $R$ | 1 |

## 4 ANALYSIS AND ADJUSTMENT

As introduced above, mutual events result from the relative positions among the Sun, satellites and the Earth (observer). Mutual eclipses between Galilean satellites happen twice every Jovian orbital period when the Sun passes through the common orbital plane defined by the satellites.

Figure 1 shows the geometrical projection of the two involved satellites during the mutual eclipse of "J1EJ2" as seen from the center of the Earth.

The flux loss during the mutual eclipse is due to the light not reaching the eclipsed satellite which is shaded by the eclipsing one, instead of the part of the light from the occulted satellite being blocked by the occulting one during the mutual occultation.

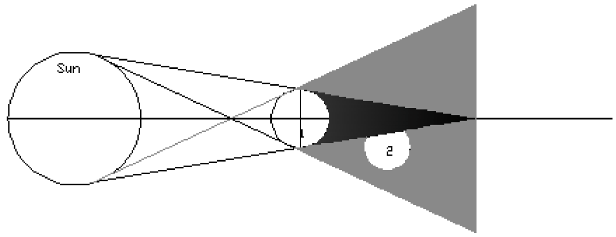


**Fig. 1** Geometry of a Mutual Eclipse of J2 Europa by J1 Io.

### 4.1 Modeling the Eclipse

Modeling a mutual eclipse is more complicated than that of mutual occultation because of the existence of the penumbra zone, which should take the Sun's limb-darkening into account. For modeling the light intensity in the penumbra zone, we used the Hestroffer and Magnan's empirical law (1998) which describes the light flux coming from a surface element in the solar disk as

$$I(\mu) = \mu^{\alpha}, \tag{1}$$

where

$$\begin{cases} \alpha \sim -0.023 + 0.292\lambda^{-1} \text{ if } \lambda \leq 2.4\mu\text{m}, \\ \alpha \sim -0.507 + 0.441\lambda^{-1} \text{ if } \lambda \geq 2.8\mu\text{m}, \\ \lambda \text{ wavelength in } \mu\text{m}, \\ \mu = \sqrt{1-r^2}, \\ r \text{ distance to the Sun's center}, R_{\odot} = 1. \end{cases} \tag{2}$$

Thus, we calculated the solar flux $i_{\odot}$ received by each point of the eclipsed satellite in the penumbra zone with the following formula (with $r$ in AU)

$$\begin{aligned} i_{\odot} = 1 - \frac{1}{2R_{\odot}^2} \left[ \left(1 - \left(\frac{r}{R_{\odot}}\right)^2\right)^{\frac{\alpha}{2}} (r - R_{\odot})(2(r + R_{\odot}) + \alpha\, r) \right]_{r'_0}^{r'_1} \\ + \frac{\alpha^2 + 6\alpha + 8}{8\pi R_{\odot}^2} \int_{r'_1}^{r'_2} r \left(1 - \left(\frac{r}{R_{\odot}}\right)^2\right)^{\frac{\alpha}{2}} \Psi(R_1, r, R) dr, \end{aligned} \tag{3}$$

where

$$\begin{cases} R_1 &= \text{radius of the first satellite}, \\ r'_0 &= \min[R'_{\odot}, \max(0, R - R_1)], \\ r'_1 &= \min[R'_{\odot}, \max(r'_0, R_1 - R)], \\ r'_2 &= \min(R'_{\odot}, R + R_1), \\ R &= \text{distance between the eclipsed satellite and the center of the penumbra zone}, \\ R'_{\odot} &= \text{Sun's radius seen from the eclipsed satellite "reduced" to the distance of} \\ & \quad \text{eclipsing satellite}, \end{cases}$$

and $\Psi$ is defined by

$$\Psi(R_1, r, R) = 2 \arctan\left(\frac{\sqrt{r^2 - a^2}}{a}\right), \tag{4}$$

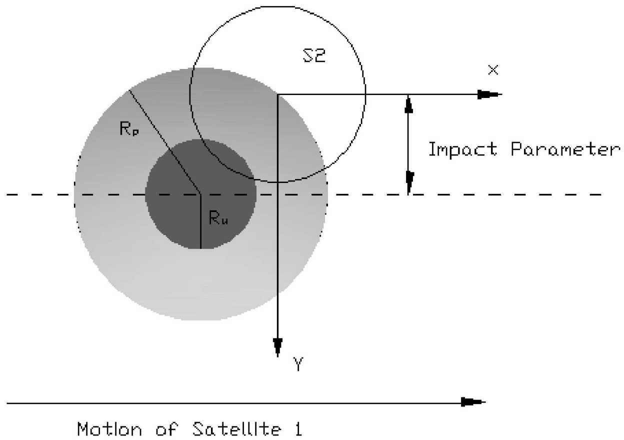


**Fig. 2** Dynamical model of the mutual eclipse corresponding to Figure 1.

where

$$a = \frac{r^2 + R^2 - R_1^2}{2R}. \tag{5}$$

Before fitting the observed light curves, the eclipsed satellite is assumed to be unmovable. In addition, the eclipsing one has a linear uniform motion relative to the other satellite (as shown in Fig. 2).

In the next step, the flux loss of the eclipsed satellite corresponding to the part of its surface in the umbra and penumbra during the event was calculated with the following formula,

$$F_{\rm loss} = \int_{A_{\rm U}}^{A_{\rm P}} (1 - i_\odot) dA + A_{\rm U} = \int_0^{A_{\rm P}} (1 - i_\odot) dA_{\rm P}. \tag{6}$$

$A_{\rm P}$ and $A_{\rm U}$ are the part of the eclipsed satellite's surface in the penumbra and umbra zones respectively. The flux drop of the satellites will be obtained after normalizing the flux to one before and after the mutual eclipse.

### 4.2 Analysis and Results

Since the dynamical model had been determined, we used the algorithm of Gauss-Newton iteration (Teunissen 8) to carry out the least-squares fit of the light curves. The initial values of the dynamical parameters were derived from the MULTISAT ephemerides available on *www.imcce.fr/sat* (Emel'Yanov & Arlot 4).

In order to get more accurate astrometric data of Galilean satellites, the effects of phase angle and light scattering over the surfaces of satellites were considered during the fitting of the light curves. In this paper, the Lommel-Seeliger scattering law (Surdej & Surdej 7) was chosen to calculate the quantities of the relative coordinates and velocities of the eclipsing satellite J1 Io with respect to the eclipsed one J2 Europa, the impact parameters and the mid-times.

Table 3 gives the detailed results of the dynamical parameters for each event, in which the first to third columns denote the observed dates, types and observed mid-times of each event, the fourth and fifth columns are the impact parameter we observed and the position angle of the eclipsing satellite relative to the eclipsed one respectively and the sixth and seventh columns are the observed values of $\Delta\alpha\cos\delta$ and $\Delta\delta$ respectively. The residuals of $\Delta\alpha\cos\delta$ and $\Delta\delta$, calculated relative to ephemeris L2 (2009) and L1 (2006) by (5), G5 by (1) and E5 by (6), which are usually expressed as $O - C$ $(x)$

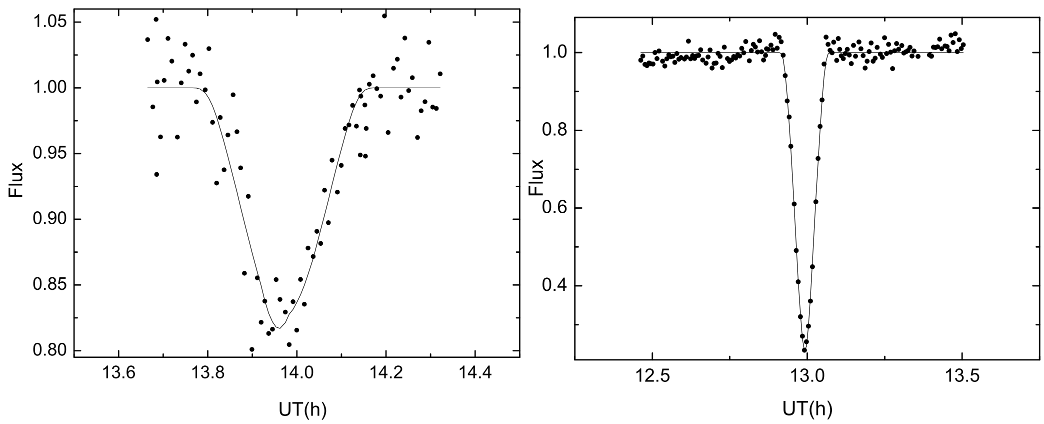


**Fig. 3** Observed and fitted light curves expressed as dots and a bold line respectively.

and $O - C$ $(y)$, occupy the next two columns. The ephemerides and the flux drops are given in the last column.

As shown in Table 2, the total flux of J1 Io and J2 Europa was calculated for the event of 20090828J1EJ2. Therefore the parameter $k$ of the albedo ratio of J1 to J2 should be taken into account during the fitting of the light curve. In this paper, the value of $k$ from 0.9 to 1.2 was chosen during the simulation, with a step size of 0.001. Finally, we performed the best simulation where the value of $k$ is 1.009.

The observed and fitted light curves, expressed as dots and a bold line respectively, are plotted in Figure 3, with the flux of involved satellites being normalized to one before and after the mutual eclipses.

## 5 CONCLUSIONS

Our results concerning our observations demonstrate the high angular resolution of the mutual events of the Jovian satellites. By comparing the $O - C$s in Table 3, we can find that the new theoretical models L1 and L2 are more accurate than G5 and E5.

During one mutual event, the longitude shifts of satellites can be deduced from the difference between the observed mid-time and the calculated one; a detailed explanation can be found in the paper of (3). The observations provided in this paper should be added to the others made during

**Table 3** Comparison of the Astrometric Results

| Date (y m d) | Type | Midtime (h m s) | Impact ($''$) | $A$ ($^\circ$) | $\Delta\alpha\cos\delta$ ($''$) | $\Delta\delta$ ($''$) | $O-C$ ($Dx''$) | ($Dy''$) | Ephemerides | Flux drop (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2009–08–28 | J1EJ2 | 13 58 7.43 ±4.3s | 0.49791 | 335 | –0.21043 ±0.0019 | 0.45126 ±0.0019 | 0.0005 | 0.0007 | L1 | 18.3 |
| | | | | | | | –0.0048 | –0.0058 | L2 | |
| | | | | | | | –0.0673 | –0.0137 | G5 | |
| | | | | | | | –0.0853 | –0.0434 | E5 | |
| 2009–09–12 | J1EJ2 | 12 59 32.28 ±0.1s | 0.22496 | 347 | –0.05060 ±0.0004 | 0.21919 ±0.0004 | 0.0105 | –0.0448 | L1 | 76.7 |
| | | | | | | | 0.0017 | –0.0432 | L2 | |
| | | | | | | | –0.0768 | –0.0699 | G5 | |
| | | | | | | | –0.0795 | –0.0688 | E5 | |

the 2009 occurrence for improving the study of dynamics of the Galilean satellites. The reduction presented here could be applied to all the observations in order to determine observed astrometric positions useful for modeling the dynamics of the system.

We look forward to the next occurrence in 2014–2015 when there will be an opportunity to acquire more data at a time when the space probes will not be able to provide data and researchers will be preparing for the EJSM mission to the Jovian system. Note that our data (photometric light curves) will be available at *http://www.imcce.fr/nsdc.*

**Acknowledgements** We would like to thank Dr. Jean-Eudes Arlot for his valuable help. We also would like to thank the staff of the 60-cm telescope team of Yunnan Observatory for their help and support in our work. This work was supported by the National Basic Research Program of China (973 Program; Grant No. 2011CB811400), and the Joint Doctoral Promotion Programme of the Chinese Academy of Science.

## References

Arlot, J.-E. 1982, A&A, 107, 305
Arlot, J.-E. 2008, A&A, 478, 285
Arlot, J.-E., Dumas, C., & Sicardy, B. 2008, A&A, 492, 599
Emel'Yanov, N. V., & Arlot, J.-E. 2008, A&A, 487, 759
Hestroffer, D., & Magnan, C., 1998, A&A, 333, 338
Lainey, V., Duriez, L., & Vienne, A. 2006, A&A, 456, 783
Lieske, J. H. 1998, A&AS, 129, 205
Surdej, A., & Surdej, J. 1978, A&A, 66, 31
Teunissen, P. J. G. 1990, Manuscripta Geodaetica, 15, 137