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Astrometric results of the mutual events between the Saturn's satellites observed at Yunnan Observatory

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ABSTRACT

The mutual eclipse of S4 Dione by S3 Tethys (Dec 23, 2009) and mutual occultation of S3 Tethys by S4 Dione (Apr 24, 2010) were observed at Yunnan Observatory during the international campaign in 2009–2010. The aim of this paper is to calculate the astrometric data of the involved Saturnian satellites during the mutual events, using a same dynamical model as proposed by Assafin et al. (2009) for the mutual occultation and a same one as proposed by Zhang and Liu (2011) for the mutual eclipse, and taking the scattering properties of the Saturnian satellites surfaces into account. Compared with the theory TASS 1.7 (Vienne and Duriez, 1995), the O–C(x) and O–C(y) are 10.1 mas, 3.4 mas for the mutual eclipse S4 by S3 and 28.4 mas, −1.3 mas for the mutual occultation S3 by S4, and with respect to the theory by Lainey et al. (2011), the results are 1.0 mas, −5.0 mas and −0.2 mas, 2.5 mas respectively.

1. Introduction

Photometric observations of the mutual occultation and eclipse between the Saturnian satellites are more rare and difficult than that of the Galilean satellites to obtain, because of the farther distance and smaller diameter of the Saturnian satellites, but it also can provide very accurate and invaluable astrometric data for the study of the dynamics of the Saturnian satellites. The photometry of the mutual events between the natural satellites has been verified to be a most effective and accurate ground-based means of obtaining astrometric data of the natural satellites.

The Sun and the Earth traverse the common orbital plane of the Saturnian satellites, that is the equatorial plane of the Saturn, every 15 years, so the observable period of the mutual events of the Saturnian satellites is 15 years.

In 2009–2010, two mutual occultations and two mutual eclipses between the Saturnian satellites that had been predicted by Arlot and Thuillot (2008), were observed at Yunnan Observatory, but only two light curves were got. The aim of this paper is to calculate several physical and dynamical quantities of the Saturnian satellites by fitting the light curves we observed. In the following sections, we provide the detailed descriptions of the observations, reductions, analysis and fitting of the light curves, and the astrometric results of these two mutual events.

2. CCD photometric observations

2.1. Observation

We used the 1-m and 60-cm telescopes at Yunnan Observatory (102°47′.3E, 25°1′.5N, altitude = 2000 m, IAU code 286), with the attached DW436 2048 × 2048 CCDs, to observe the mutual eclipse and the mutual occultation of the Saturnian satellites on Dec 23, 2009 and Apr 24, 2010 respectively. The effective field of view of the 1-m telescope at the Cassegrain focus is about 7 × 7 square arc min, and that of the 60-cm telescope is 12 × 12 square arc min. During the observations, a Johnson R filter was used. The frequency of the readout we chose is 1 μs/pixel, and then one data point was got for almost every 7–8 s. Each data point corresponds to one flux information of the satellites involved. Table 1 shows the properties of both the 1-m telescope and the 60-cm telescope at Yunnan Observatory.

2.2. Reduction

During processing the images, each image was bias-corrected and flat-fielded, and then the curves of flux variations relative to UT time were obtained for each event. Each image observed during the mutual events corresponds to one flux data point of the satellites involved. Table 2 shows the details of our observations and reductions, where S3, S4, and S6 are the Saturnian

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Table 1
Properties of the 1-m and 60-cm telescopes at Yunnan Observatory, with the attached CCDs.

Telescope	F-length (mm)	CCD FOV	Size of pixel	Size of CCD	Size/ pixel
1-m	13 000	$7' \times 7'$	13.5 μm × 13.5 μm	2048 × 2048	$0''.21$
60-cm	7500	$12' \times 12'$	13.5 μm × 13.5 μm	2048 × 2048	$0''.35$

Table 2
Observational details of the mutual events observed at Yunnan Observatory in 2009 and 2010.

Date y m d	Type	Ref	Telescope	Exposure (s)
2009 12 23	S3eS4	S6	60-cm	1
2010 04 24	S4oS3	S6	1-m	1.5

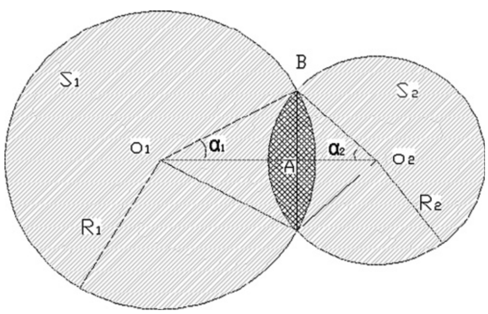

Fig. 1. Geometry of a partial mutual event where the disks S_1 and S_2 of radius $R_2 < R_1$ partially intercept each other with an area A, S_1 and S_2 representing the two Saturnian satellites involved.

satellites Tethys, Dione, and Titan, respectively, 'S4oS3' means the event of Dione occults Tethys, 'S3eS4' means the event of Tethys eclipses Dione. 'Ref' indicates the satellite used as a reference for the photometry, which in this paper is Titan for the events between Tethys and Dione. 'Telescope' indicates the apertures of the two different telescopes used whose complete descriptions are provided in Table 1. 'Exposure' gives the exposure time of each event.

3. Analysis and adjustment

As mentioned above, mutual events depend on the relative positions of the Sun, satellites, and the Earth (observer). Figs. 1 and 2 show the geometrical projection of the two satellites involved during the mutual events, as seen from the center of the Earth for the mutual occultation and seen from the center of the Sun for the mutual eclipse respectively.

3.1. Dynamical model

3.1.1. Modeling the occultation

The model proposed by Assafin et al. (2009) is used to fit the observed light curve of the mutual occultation, with an assumption being made, what is that the occulted satellite is assumed to be unmovable, while the occulting one has a linear uniform motion relative to the occulted one (as shown in Fig. 3).

During a mutual occultation, the flux variation of the satellites involved is mainly determined by the occulted area A (as shown in Fig. 1) of S_2 by S_1 and the different surface properties of them. In spite of the surfaces of satellites being nonuniform, when the

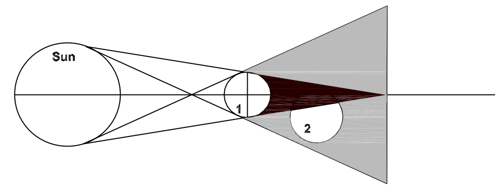

Fig. 2. Geometry of a mutual eclipse of S_2 by S_1 with the radius $R_1 < R_2$.

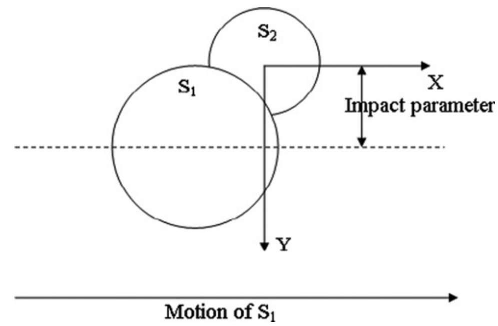

Fig. 3. Dynamical model of the mutual event corresponding to Fig. 1.

value of albedo ratio of the occulting to the occulted satellites is a constant during fitting the mutual occultation because of their short duration, the corresponding formula used to perform the fitting of the light curve is given as below. Eq. (1) shows the expression of flux variation of the satellites involved, which has been normalized to 1 before and after mutual occultation, where F_{1o2} represents the flux of the satellites involved during the mutual occultation, F_{1+2}, that of before and after the mutual event, and R_1, k_1 and R_2, k_2, the radius and albedos of S_1 and S_2, respectively, such that

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

where,

$$\cos \alpha_i = \frac{R_i^2 - R_j^2 + d^2}{2R_i d} \tag{2}$$

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

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

Eq. (3) corresponds to Fig. 3, in which d and d_0 are the relative distance and the impact parameter, v is the velocity of the occulting/eclipsing satellite from to the occulted/eclipsed one, t and t_0 are the time of observation and the mid-time respectively.

3.1.2. Modeling the eclipse

Modeling a mutual eclipse is more complicated than that of a mutual occultation because of the existence of the penumbra zone, caused by the limb darkening effect of the Sun. The same model and formulas as introduced by Zhang and Liu (2011) were adopted to fit the mutual eclipse of Dione by Tethys. Fig. 4 shows the dynamical model corresponding to Fig. 2.

3.2. Photometric model

In order to get higher accuracy astrometric data of the Saturnian satellites, the effect of the scattering properties of the surfaces of the Saturnian satellites is considered during the fitting of the light curves, so following photometric function (shown as Eq. (4)) is proposed, in this paper, to calculate the quantities of the