THE RESULTS OF OBSERVATIONS OF MUTUAL PHENOMENA OF THE GALILEAN SATELLITES OF JUPITER IN 2009 AND 2015 IN NIKOLAEV ASTRONOMICAL OBSERVATORY

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ABSTRACT. The Earth and Jupiter once in 6 years have simultaneous passage of the ecliptic plane due to their orbital movement around the Sun. This makes it possible to observe the mutual occultations and eclipses in the Galilean satellites of Jupiter.

We took part in the observational campaigns of the mutual phenomena in 2009 and 2014-15. The observations were made with a B/W CCD camera WAT-902H at the telescope MCT (D = 0.115 m, F = 2.0 m) of the Nikolaev Astronomical Observatory. The light curves of mutual phenomena in the satellites of Jupiter were obtained as a result of processing photometric observations. The exact moments of maximum phases and the amplitudes of the light variation have been determined from the analysis of the light curves.

The data sets for the light curves have been sent in the IMCCE (Institute de Mecanique et de calcul des ephemerides, France) that coordinates the PHEMU campaigns.

Keywords: Jupiter: Galilean satellites: mutual phenomena

1. Introduction

Twice in orbital period which is 11.86 years, the transit of Jupiter through the nodes of its equator provides the opportunity for an edge-on view of its equatorial plane from the inner solar system. Since inclination of the orbital planes of the Galilean satellites to the planet's equator is very small the series of mutual phenomena (PHEMU) in Jovian satellites system occurs during about 9 month every 6 years.

The most observed PHEMU are eclipses and occultations. During a mutual eclipse one satellite passes through the shadow of the other satellite or Jupiter. At an occultation one satellite passes in front of another as seen from the Earth. The absence of atmosphere on the Galilean satellites permits very accurate observations allowing the determination of the time, duration and the amplitude of the observed phenomenon. The high precision photometric observations of PHEMU are an effective way of obtaining new astrometric data which has great potential in studies of secular variations and problems related to the resonances in mean motion, improve the theoretical models of the orbital motions and to determine the tidal effects in the dynamics of the Galilean satellites which not yet put into evidence.

We took part in two observational PHEMU campaigns coordinated by the IMCCE (Institute de Mecanique et de calcul des ephemerides, France). The results of the photometric observations of the Galilean satellites of Jupiter in the 2009 and 2015 are presented here.

2. Instruments for observations and reduction methods

The mutual phenomena in the Galilean satellites system of Jupiter can be easy observable. These phenomena have short duration (the mean duration of events don't exceed 10 minutes), high brightness (the Galilean satellites are 4-6 magnitude) and the magnitude drop can reach even more than one magnitude.

The observations of the PHEMU were carried out at Multichannel telescope (MCT) of the Nikolaev Astronomical Observatory (observatory code 089). Telescope MCT (D = 0.115 m, F = 2.0 m) was equipped the B/W CCD camera WAT-902H (752x582, 8.6x8.3 mkm^2), which allows to get 25 images per second. The size of field of view is 11.12′x8.3′ and scale – 0.89x0.86″/pix, that allows to get images of Jupiter with four Galilean satellites simultaneously. The standard red glass filter marked RG-19 was used to reducing the light flux coming from the too bright Galilean satellites and Jupiter. Each image dated in UTC (Universal Time) with accuracy 0.001 sec by GPS.

Ephemerides for observation of mutual phenomena, calculated for Nikolaev Astronomical Observatory (089) were taken from the site of IMCCE (http://www.imcce.fr/hosted_sites/saimirror/nsszph515he.htm). According to the calculated ephemeris it was predicted 100 mutual phenomena in the Galilean satellites of Jupiter in 2009, and 186 in 2014-2015. The photometric observations of 13 mutual phenomena were carried out in 2009 and satisfactory light curves for 6 of them were obtained. During 2015 the observations of 5 mutual phenomena were performed and satisfactory light curves for 2 phenomena were obtained.

The obtained images have been processed with a Tangra software, version 3 (http://www.hristopavlov.net/Tangra3). The software allows to measure of the numerous successive images automatically. The aperture photometry method was used for processing. Due to the high brightness of Jupiter the most relevant processing step was choosing of the best model to determine of the sky background. The irregularities of background on the image can significantly impact on the measurement of the luminous flux of the investigated object.

The Average, Median, Background Mode, 3D Polynomial Fit and PSF-Fitting methods are implemented in Tangra software to account for the effect of sky background. The flux of the sky background nearby the investigated object was calculated by various methods and a light curves were plotted. The light curves of background flux for the occultation J2 (Europe) by J1 (Io) on August 5, 2015 derived by different reduction methods are shown in Fig.1. As can be seen, the 3D Polynomial Fit model shows the actual change of the sky background on the image caused by the displacement of the object towards to Jupiter during phenomenon. Other models due to nonoptimal algorithm of calculating do not show such changes in the background.

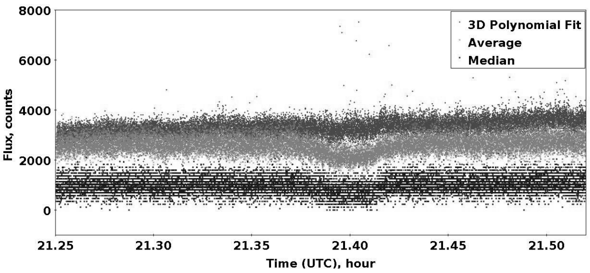

Figure 1: The light curve of background flux derived from different reduction methods.

Such analysis have been performed for each of the obtained observational series and the 3D Polynomial Fit model showed the lowest values of the relative errors of the sky background (12%). The statistical information of measurements of the sky background by various methods is given in the Table 1.

Table 1. Statistical information for background reduction method.

Reduction method	**Average value,** counts	**Standard deviation,** counts	**Relative error,** %
Average	2605.2	323.5	12.4
Median	965.6	289.5	29.9
Background Mode	2495.8	876.2	35.1
3D Polynomial Fit	3287.5	394.6	12.0
PSF-Fitting Background	3641.7	1790.1	49.2

More than 20 thousand images have been obtained during observation for each phenomenon. The measurements have been averaged by four points to increase the accuracy of results. It is also allows to reduce the amount of data to be sent to the IMCCE coordinating observation campaign (according to requirements only 10 thousand points are accepted).

In some cases, satellites are located close enough to each other and their light fluxes are partially overlapped. For such cases the total fluxes from related objects have been measured according to the method (F. Colas, JE Arlot, 2008).

3. The results of observations

The light curves of all Galilean satellites seen in the image were obtained because other Galilean satellites have been used as the photometric reference sources during the phenomenon. The light curve of the eclipse of J1 J2 (Io-Europe) derived from observation carried out on October 3^{d}, 2009 are presented in Fig.2. The background flux has been removed and clear flux averaged in 4 points (Fig.2, top). It should be noted that last part of light curves derived during phenomenon on all of observed satellites has some fluctuations. It caused by atmosphere nebulosity and the flux of satellite J2 (Europe) have been divided by flux of J1 (Io) in order to remove it. Normalized flux of J2 (Europe) by J1 (Io) presented on Fig.2, bottom.

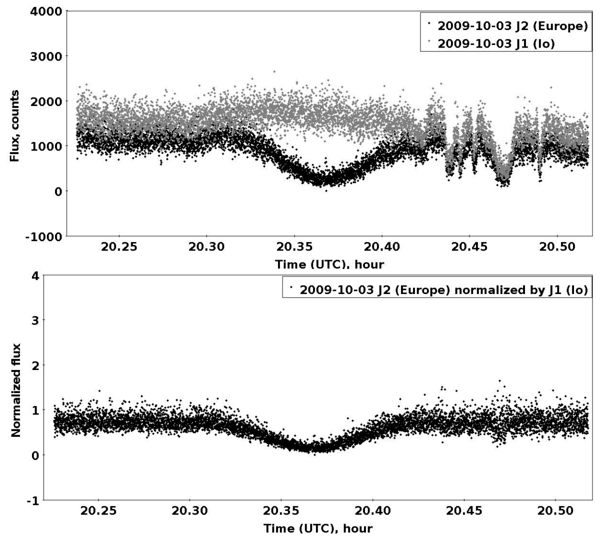

Figure 2: The light curve of eclipse J2 by J1 occurred October 3^{d}, 2009. Top part presents clear fluxes of J1 and J2. Normalized flux satellite J2 by J1 at bottom part.

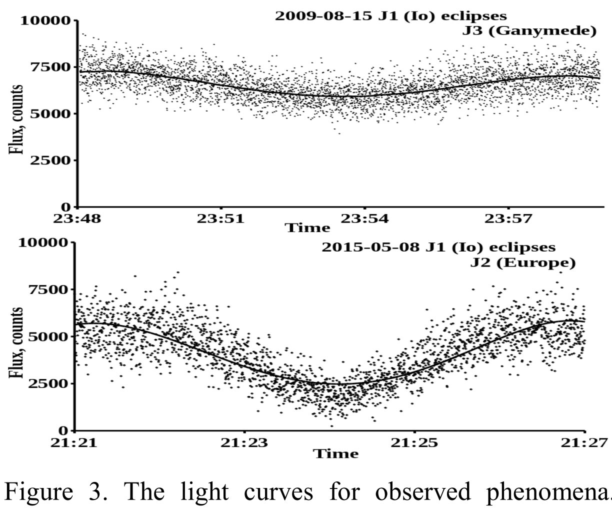

Figure 3. The light curves for observed phenomena. Solid line corresponding for approximating 4 degree polynomial function.

Unfortunately the weather conditions were not always stable during the observation of the phenomenon. The light curves, which were obtained from observation without any atmospheric fluctuations during phenomenon, have been considered as satisfactory. The approximation of such light curves has been performed by a 4 degree polynomial, which showed the smallest residuals with the actual curve. The obtained light curves and their approximating functions (solid line) of the mutual phenomena are presented in Fig. 3.

For events with satisfactory light curve the moments of maximum phase have been determined as extremes of selected approximating function. The magnitude drops for the moments of maximum phase of phenomena have been measured. Table 2 presents the predicted and determined data for the observed mutual phenomena in Nikolaev on MCT in 2009 and 2015.

Table 2. The moments of maximum phases and magnitude drop of the mutual phenomena predicted by IMCCE and observed in Nikolaev at MCT in 2009 and 2015.

Date (UTC)*	Type *	Predicted start time (UTC)*	Predicted end time (UTC)*	Expected magnitude drop *	Maximum phase (UTC)	Mag. drop
2009-08-15	1E3	23:48:00	23:59:02	0.450	23:53:32	0.26
2009-08-17	1O3	20:57:55	21:10:37	0.624	21:04:15	0.55
2009-08-17	1E3	21:08:39	21:22:26	0.436	21:15:27	0.27
2009-08-24	1O2	23:23:12	23:38:57	0.626	23:31:09	0.47
2009-10-03	1O2	18:26:41	18:33:03	0.189	18:30:09	0.23
2009-10-03	1E2	20:18:12	20:26:01	0.613	20:22:03	
2015-05-08	1E2	21:21:26	21:26:53	0.572	21:24:04	
2015-06-09	1E2	19:39:10	19:44:54	0.307	19:41:54	0.37

* Data taken from ephemerides calculated by IMCCE (http://www.imcce.fr) for Nikolaev Astronomical observatory (IAU code 089).

4. Conclusions

The instrumental preparation and photometric observations of the mutual events in the Jovian satellites system were carried out at Nikolaev Astronomical Observatory in 2009 and 2015 PHEMU campaigns. The relative photometry was performed and six satisfactory light curves were obtained. The moments of the maximum phases of events and the values of magnitude drop at maximum phase were estimated.

The comparison of the obtained time moments from our observations with the ephemeris calculated by IMCCE shows differences about from 0.5 to 1 minute.

The results of observations have been sent to the IMCCE for adding to international database and further analysis.

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