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Photometric observations of the mutual phenomena of the Galilean Satellites of Jupiter in 1997 and 2003 at the Royal Observatory of Belgium [1]

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[1]Tables 3–22 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.125.5) or via http://cdsweb.u-strasbg.fr/Abstract.html.

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Abstract. In this paper we describe the observations of the mututal phenomena of the Galilean Satellites of Jupiter performed at the Royal Observatory of Belgium, as part of the PHEMU97 and PHEMU03 campaigns. The paper describes the observational technique, the data reduction and summarises the results obtained. The tables with the data are available at the CDS.

Key words. Methods: data analysis – Methods: observational – Eclipses – Occultations – Planets and satellites: individual: Jovian Galilean Satellites

1. Introduction

Eclipses, occultations and transits of the Galilean satellites are well-known phenomena. In each of these phenomena, Jupiter and one of its satellites are involved. Less known are the mutual phenomena of the satellites where one satellite eclipses or occults another one. These phenomena occur only when the Earth (for the occultations) or the Sun (for the eclipses) is nearly in the orbital plane of the satellites. Thus, these phenomena take place only during 'seasons', which last about one year and reoccur about every six years.

The interest in observing the mutual phenomena is to better determine the positions of the satellites. The accuracy in position that can be achieved by analysing photometric observations of the satellites involved in a mutual event is much better than direct astrometric measurement, and also much better than what could be achieved by observing normal events (involving Jupiter), since the light curve obtained from a mutual event is not affected by a complex atmosphere, as is the case with a light curve obtained from an event involving Jupiter. Under the best conditions, and taking into account the surface features of the satellite (especially when the occulted or eclipsed satellite is Io), a positional precision of 8 kilometers can be achieved (Arlot 1997).

Therefore, since 1973, at each passage of the Earth and the Sun through the orbital plane of Jupiter's satellites, there have been campaigns to observe the mutual events of the Galilean Satellites. Arlot (1997) gives more details about previous campaigns, and Aksnes (1997) gives details about the reduction of the observations.

The Royal Observatory of Belgium at Ukkel took part in both the PHEMU97 (the events of the 1997 season) and PHEMU03 (the events of the 2003 season) campaigns. In 1997 a series of problems had to be solved before we could start to observe. Therefore, the first event observed was only in September 1997, while the last observable event was in November 1997. Since in 1997 Jupiter was at a declination of $-18°$ only a limited number of events could be observed from Ukkel, at a northern latitude of almost 51°, and all events were low in the sky, so that the noise in the light curves obtained is mostly due to seeing effects. In 2003, we could learn from the problems encountered in 1997, and we adjusted our observing strategy on a number of points. Since Jupiter was then at a declination of $+18°$, more events were observable, and we could make a more severe selection, observing only those events that would give the best results.

2. The observations

2.1. The telescope and the detector

For the observations we used the Ukkel Schmidt telescope (main mirror of 1.20 m, focal length of 2.12 m, corrector plate of 0.85 m), equipped with a Princeton CCD camera with a KODAK-chip in the prime focus. The chip contains 2048×3072 pixels of 9 μm $\times$ 9 μm. This corresponds to a pixel size of $0.9'' \times 0.9''$, and a field of view of $30' \times 45'$. This chip can be read out at 430 kHz or 1 MHz. This telescope-camera combination is not ideal for doing fast photometry, but the camera had been bought with the main intention of doing astrometric observations of minor planets. In order to obtain useful light curves of PHEMU phenomena, we had to set up special observing techniques.

2.2. Reading out the CCD

At a read-out speed of 1 MHz, the full chip takes 6 seconds to be read out. To get a resolution of several images per second this had to be speeded up. Moreover we found that it would be very difficult to get the timing better than 1 image, so that to achieve a timing accurate to 0.1 second the only solution was to take 10 images per second. With a total of up to more than 50 minutes of observation per phenomenon this means up to 28 000 images per phenomenon. However, in order not to get all kinds of problems the total amount of data per phenomenon could not be larger than a few tens of Megabytes in 1997. In 2003, with more powerful computers, 100 Megabytes was still manageable.

To increase the frequency of the images, and reduce the amount of data, two approaches are possible. The first is to select windows around the objects of interest, the second to use binning. Both of these approaches have their own problems. The biggest danger of binning is that images may saturate for bright objects. Since saturation of the images makes any photometry impossible, we decided not to use any binning. However, using windows of interest does not solve the problems completely. Just throwing away the part of the image outside the windows of interest takes more time than the acquisition speed of 10 images per seconds allows.

Therefore, we had to use a more sophisticated way of reading the chip. The chip was defined to contain only 16 rows, rather than the 2048 real ones. Thus, the camera, after each image shifted all charges by only 16 rows, and read out only the bottom 16 rows of the chip. The time saved by shifting only 16 of the 2048 rows was enough to allow an acquisition speed of 10 images per second. At this speed it is of course not possible to open and close the shutter, therefore the shutter remained open during the whole observation, including the read out. The drawback of this method is that, whereas the exposure time for the objects is only around 0.1 second, for the sky background and the dark current it is in fact the time for a shift over the whole array, corresponding to $2048/16 = 128$ images, or of the order of 14–15 seconds. This causes (especially for faint objects) a considerable loss in signal-to-noise ratio. But in the case of the satellites of Jupiter, the noise is dominated by seeing effects, so that this adverse effect is less prominent. A second requirement is that there was no other star to be on the same column as the observed satellite, and particular care had to be taken that Jupiter and its satellites were not aligned parallel to the columns of the CCD (the y-axis of the image). And third, one had to be aware that read-out of the actual images of the satellites was delayed by the time needed to shift the charges, 16 rows at each read-out, all the way to the shift register of the CCD chip. This caused a delay between the real observation time and the display on the screen, which could be up to 15 seconds, depending on the y position on the frame. In particular, when guiding corrections were applied the result became visible on the screen only several seconds after the actual correction, and one had to be very careful not to overcorrect.

To reduce the amount of data, windows were defined, one around the satellite being involved in the phenomenon, and one around another object as a reference. In most cases this reference object was another satellite of Jupiter. In the PHEMU97 campaign we defined the windows to be 31 pixels wide. However, we learned from this campaign that this was too small. Using such small windows gave rise to two problems. The first is that there is a non-zero risk of having one of the satellites drifting out of the window (e.g. due to tracking errors) during the observation; the second is that even with the satellite entirely inside the window, there was sometimes not enough sky background left to set up a reliable model of the sky background. Therefore, in the PHEMU03 campaign we defined the windows to be 60 pixels wide, leaving more sky background pixels for modelling. The drawback of these larger windows is that it was more difficult to keep Jupiter out of the windows, or even not too close to the windows. If Jupiter was close to the window, the binning of the pixels just outside of the windows (for faster readout of pixels not to be saved) could cause blooming into the window.

2.3. The reference object

In order to be as independent as possible of variations in sky transparency (this was expected to be very variable during the observation, due to the variable weather conditions and in 1997 due to the low altitude of Jupiter), a reference object had to be monitored at the same time as the satellite(s) involved in the phenomenon. Usually this was another satellite of Jupiter.

However, in one case (in 1997), no other satellite could be used. Since the phenomenon was an occultation, the two satellites involved in the phenomenon could not be separated. The other two satellites were invisible because they were involved in an eclipse, transition or occultation by Jupiter. There was a 6th magnitude star slightly less than 30 arcminutes from Jupiter, so that Jupiter and the star could just be positioned on the same frame, and this star was used as a reference, but the distance was too large, so that the correlation in sky transparency between the satellite and the reference star was very poor.

In one other case (in 2003), there were two phenomena too close to each other to redefine new windows and generate time flashes (see section 2.5) between the phenomena. In that case, there was only one possibility, monitoring both satellites involved in a phenomenon at the same time, and using the satellite involved in the second phenomenon as a reference object for the first phenomenon and vice versa.

2.4. The filter

Some of the phenomena took place very close to Jupiter. Since Jupiter is very bright, one could expect a significant sky background that would not even be constant over the image. In order to reduce this sky background we purchased a special-purpose filter, with a half width of about 20 nm, centred at 892 nm, the methane band, in which Jupiter is very dark. However, this filter also reduces the brightness of the satellites, and hence also the signal-to-noise ratio. For some of the phenomena in 1997, when Jupiter was too low in the sky, or when the sky was too nebulous, this filter would have absorbed too much light and too little signal would have been left to do photometry. Therefore, for each phenomenon individually we decided whether to use the filter or not, depending on the distance between the satellites and Jupiter, the elevation of Jupiter above the horizon and the quality of the sky. In 2003 we only observed phenomena high enough in the sky, so that we could use the filter systsematically for all phenomena.

If no filter is used, the response of the CCD-camera is close to the R band.

2.5. The timing of the images

Getting an accurate timing was a special problem. Because the whole observation is stored as one single file containing many images, but only one header, the software stores in the header of the image only the time of the first image. Moreover this is stored with a precision of only 1 second, which is insufficient. There is a possibility to trigger the camera. This could give a very good timing for the first image, but not for the next images. The problem is that we did not know the exact speed of the acquisition, nor did we not know whether this speed was stable.

The only way to overcome this problem was to put time marks on the images themselves. With image sizes of only 62×16 pixels or 120×16 pixels it is of course not possible to put additional text or so. Therefore we decided to generate light flashes at very precise instants, in this case at the exact minute UTC. These flashes were generated with 3 infrared LEDs, and lasted significantly less than 0.1 second. The increased background of some of the images gives a timing of the image with a precision of 0.1 second. Since the full CCD is completely read out only after 128 images, each flash affected 128 images (or 129 if the flash occurred during the shift of the charges).

Since such a flash was generated by a punctual light source and without using the optics of the telescope, the flat fielding of the light generated by such a flash is completely different from the flat fielding of the satellites, which is in turn different from the flat fielding of the sky background. In particular, such a flash acts more or less like a camera obscura and projects a sharp image of the front window on the chip with clear diffraction rings around each little piece of dust. It would thus not be possible to flat field images affected by flashes. Therefore, in order not to disturb the observations themselves only six flashes were generated well before each event, and six well after each event.

In a few cases in 2003 the flashing mechanism failed. It was then only possible to do the timings by hand. With two observers, one was looking at a UTC clock, and ticking on the window of the control room at the seconds 55, 56, 57, 58, 59 and 00. The other observer meanwhile looked at the screen and noted the number of the image being displayed at the exact moment of the sixth tick. Then both observers exchanged their role, to minimise personal effects. This way also six timings were recorded before and six after each event. With a test during the day, when timings were recorded both ways (ticks and flashes), we found that this method also gave a precision of 0.1 second.

2.6. Selecting the phenomena

During the PHEMU97 campaign, due to its declination the maximum elevation that Jupiter could reach in the Ukkel sky was 21 degrees. Since the Ukkel sky degrades very rapidly with decreasing elevation, we observed only phenomena not too far from the meridian (although 1997 09 29 3 ECL 2 was observed at only 12 degrees altitude). We also excluded phenomena taking place too close to Jupiter. However, we did not place a constraint on the flux drop.

Since Jupiter was at higher declination during the PHEMU03 campaign than was the case for the PHEMU97 campaign, there were more observable phenomena from Ukkel and we could be more severe in the criteria for selecting the phenomena. As a rule, we wanted to have Jupiter at least 40 degrees above horizon (with 2003 02 17 1 OCC 2 at only 32 degrees elevation), the sun at least 9 degrees below horizon, the phenomenon taking place far enough from Jupiter (1.3 Jupiter radii turned out to be too close), and the flux drop deep enough to be measurable.

3. The reductions

3.1. Dark frames and flat fields

For each observation, specific windows were defined around the satellites involved. The position of the windows was dependent on the position of the satellites and their relative motion. This means that the dark current and the flat fielding of the sky background were different for each observation. A dark frame and a flat field was taken for each observation in exactly the same way as the phenomenon observed, except that they were restricted to only 1000 images. Since for each image of the same observation the dark current and the flat fielding is considered to be the same, both were averaged over the frames 129–1000 (the first 128 images cannot be used, because then the sky background and the dark current are gradually building up), producing one dark frame and one flat field of 62 $\times$ 16 pixels or 120 $\times$ 16 pixels each. The satellites, however, were not spread over many pixels, but illuminated a few particular pixels on the chip. Therefore, for flat fielding the satellites, a normal flat field (a full image of 3072×2048 pixels) had to be used and we had to know on which pixel exactly the satellite was positioned.

The first column of each window had to be removed. At readout, pixels not stored in the final image (pixels not in the defined windows) still have to be shifted. To speed up this shift these pixels are binned, and this left residual signal in the first column, in fact a sort of blooming, which could not be removed by the usual dark subtraction and flat divide. The first line shows the same effect, although to a lesser extent. But since the sky model used is independent of the y-coordinate (see section 3.4) this is not really a problem. Moreover this line could not be eliminated, because often one of the satellites is positioned on this line. This is the case if the vertical distance between two satellites is around 8 + a multiple of 16 pixels. In that case vertically both satellites could not be positioned at the same time inside a window.

3.2. Location of the satellite

To find the position of the satellite on the CCD, one has to find on which image the satellite first appears. In fact, if the whole film with all images is converted to one single two-dimensional image, all subsequent images of the satellite will be separated vertically by about 16 pixels. The y-position of the first image of the satellite will be identical to the y-position on the CCD. The position of the second image will be shifted by 16 pixels compared to the position on the CCD. In general, if the n-th image is positioned on pixel y of the combined image, then its position on the CCD was $y - (n - 1) \times 16$. This position must be known in order to be able to flat field the image of the satellite.

If clouds caused the satellites to disappear, we had to estimate the number of missing images. This can be done by measuring the distance in pixels between two visible images. This should be close to a multiple of 16. The more images are missing, the more this distance will deviate from a multiple of 16, due to tracking errors of the telescope. When the error becomes as large as 8 pixels, then there is an ambiguity in the number of missing images, and thus there may be an error of 0.1 second in the timings of subsequent images, and of 16 pixels in the position of the satellite on the chip.

There was one case where we did not see the satellites on the first image. To find their position on the chip, we had to investigate some full frame images taken some time before the event. By estimating the drift of the telescope and the motion of the satellites, we could still make a ”best estimate” for the position where the satellite should have been on the chip.

3.3. Timing

For the timing, the average sky background was computed for each image. A sudden increase in the sky background meant that a flash started. 128 images further a drop of the same amplitude occurred, marking the end of the flash. This way, it was found that the frequency of images was 610.77 images per minute for the PHEMU97 campaign and 534.55 images per minute for the PHEMU03 campaign (new software on the PC explains the difference in acquisition speed). Moreover, this acquisition speed turned out to be very stable.

The stability of the acquisition speed helped us quite a lot in the PHEMU97 campaign because it turned out that there had been many false flashes caused by induction by the electric equipment. However, a good flash, one that occurred on the exact minute UTC, was easily identified by the fact that there had to be another one 610 or 611 images further or prior. In the PHEMU03 campaign almost no false flashes occurred, and when present, they could easily be identified.

By identifying the image number of each first image with increased sky background, and using the corresponding minute, a linear transformation could be established between image number and time. For the timing of the satellite images, again the count of the satellite images had to be used.

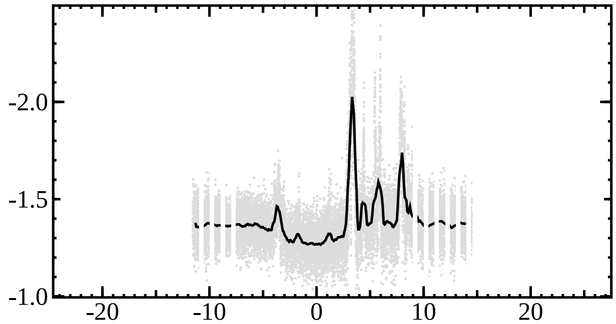

Fig. 1. The lightcurve of phenomenon 1997 09 19 4 OCC 3.

3.4. Modeling the sky background

Modeling the sky background turned out to be the most difficult part of the reduction in the PHEMU97 campaign. Clearly, improvements could be made, and therefore the approach in the PHEMU03 campaign was rather different from the one used in the PHEMU97 campaign.

In the PHEMU97 campaign we had defined windows of no more than 31×16 pixels around each satellite, while a satellite image was assumed to occupy 16×16 pixels on the image. If the satellite is well centred on the window, there are 7×16 pixels left on both sides to model the sky background. However, centring the satellite is not always possible. First, there are some imperfections in the guiding of the telescope as well as the effect of the seeing. Second, during the observation (up to 40 minutes) the relative distance of the satellites changed, while the relative distance between the two windows could not be modified. Therefore, the relative distance between the two windows was chosen to be the relative distance of the two satellites at the maximum of the phenomenon. This often causes the satellites to lie along the border of the windows at the beginning and the end of the phenomenon, leaving only very few pixels on one side to model the sky background. Third, keeping the satellite at the right place was not easy because each motion of the telescope was seen on the screen only some time later (up to 10 seconds) depending on the position of the satellite on the chip. As a consequence sometimes a satellite drifted to the border of the window.

To model the sky background a different approach had to be taken, depending on whether the observation had been done with the methane filter or not. If the filter had been used, the quantity of sky background was low and smooth enough to assume that it was linear in x (linear in the distance to Jupiter) and constant in y (the direction more or less perpendicular to Jupiter). During the observation, however, there were very large variations in the quantity of sky background and the transparency of the sky. This was due both to the rapidly varying weather conditions and the low altitude of Jupiter (usually between 15 and 20 degrees). Therefore, we fitted a polynomial, linear in x, constant in y, and third degree in the image number to 150 successive images, and applied this model the central 50 images of these 150. This process was repeated iteratively each time with a shift of 50 images, until the whole film had been processed. In a few cases it turned out that a linear model in x was not adequate to model the sky background, and in that case we switched to a second degree polynomial. To model the sky background, the x-coordinate is referred to a coordinate system that is fixed to the satellite (which can move on the chip) and not to the CCD. This is because we assume that the sky background is dependent on the distance to Jupiter, and that the satellite-Jupiter distance may be considered to remain constant over 150 images (about 14 seconds), whereas due to guiding corrections, the satellite can move considerably on the chip.

If no filter had been used, the sky background was highly non-linear in x. Therefore we used by default a third-degree polynominal to fit the sky background in x. The approach in y and in the image number remained the same as in the case of an observation with the filter. In some cases it turned out to be very difficult to model the sky background when the satellite got too close to the border. Not enough pixels of sky background were left on that side to fit a third degree polynomial, causing the model of the sky background to suffer from bad extrapolation. In those cases a second degree polynomial fit was tried, and if that did not help, as a last resort the box surrounding the satellite was reduced from 16×16 pixels to 12×16 pixels, leaving more sky background. If that did not help either, the portion of the film in which the sky background could not be modeled was removed from the final light curve.

Learning from the mistakes in the PHEMU97 campaign, to model the sky background, we followed much better procedures in the PHEMU03 campaign. First, we used windows 60 pixels wide, such that there is enough sky background left in the image after masking the image of the satellites. Second, since the observed phenomena

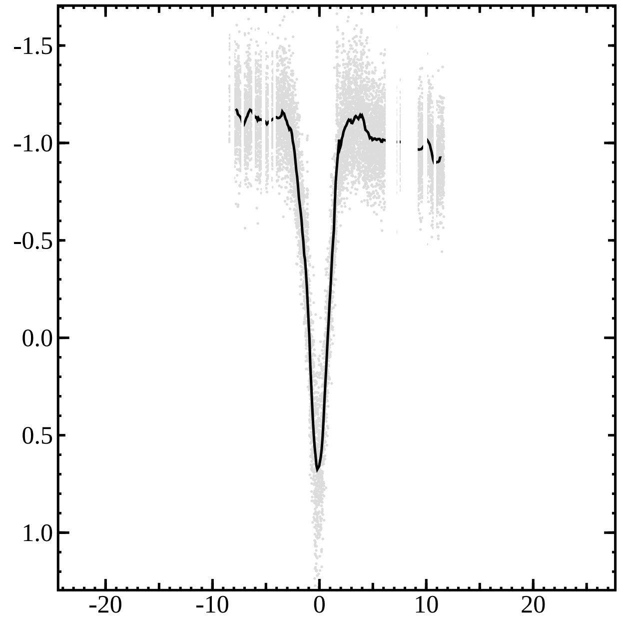

Fig. 2. The lightcurve of phenomenon 1997 09 21 3 ECL 1.

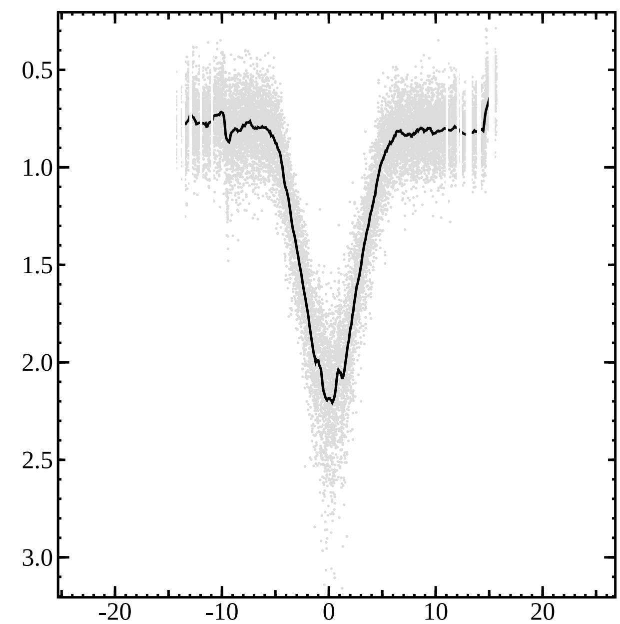

Fig. 3. The lightcurve of phenomenon 1997 09 22 3 ECL 2.

were high in the sky and produced enough signal, such that we could use the methane band filter for all phenomena, we could use a linear model in *x* for all events. Third, rather than removing a window with a fixed size around each satellite, we used software automatically determining for each pixel whether it contained sky background or an object. This software uses a principle of searching for gradients in the image. The advantage of this method is that it will remove no more pixels than strictly necessary around each satellite, but it will also efficiently remove stars that may appear on the frames, Jupiter or blooming by Jupiter that sometimes is visible, as well as effects produced by cosmic rays. Thus a maximum of useful pixels with sky background is left, and modeling the sky background this way never failed.

The following portions of each film could not be used, because the sky background could not be modeled, and was consequently left out from the final light curve:

– The first 128 images, because the sky background builds up during this start up phase.

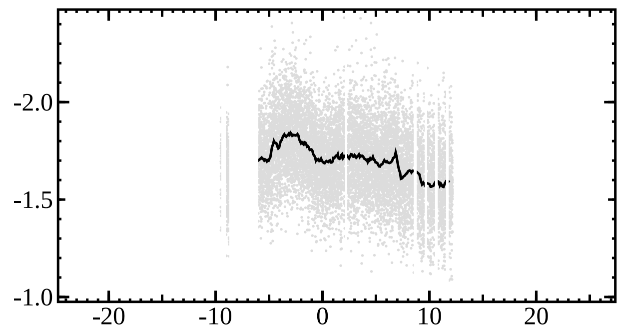

Fig. 4. The lightcurve of phenomenon 1997 09 25 1 OCC 3.

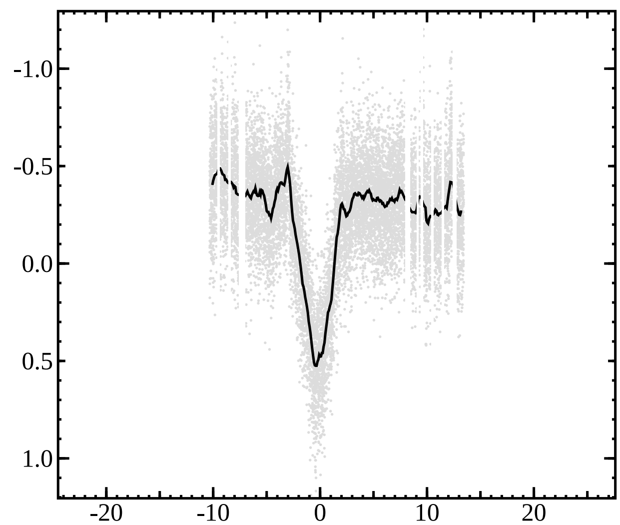

Fig. 5. The lightcurve of phenomenon 1997 09 25 1 ECL 3.

- The next 50 images. The first model of the sky was created using images 129 through 278, and applied to images 179 through 228. This means that there is no model to be applied to the images 129 through 178. The first image for which the sky background can be modeled is consequently image 179. This does not mean that the 179th image of the satellite is on this image, because, depending on the position on the chip, the first image of the satellite could appear anywhere between the first and the 128th image of the film.
- The images affected by flashes.
- The last fifty images, and the excess images after the last model (no attempt was made to apply another model for less than 50 images left).
- The images for which all attempts to fit a model for the sky background failed (only for the PHEMU97 campaign).

3.5. Photometry

The final photometry was obtained by summing the flux over the whole region containing a satellite. No attempt was made to fit a particular PSF (point spread function). This would have failed anyway, because of seeing effects. The shape of the images of the satellites is highly variable from one image to the next. In the PHEMU97 campaign the flux is summed over a box with a fixed size; in the PHEMU03 campaign better software determined which pixels contain the signal from the satellite, and the summing of the flux was restricted to these pixels. This approach turned out to give slightly better results in a few cases.

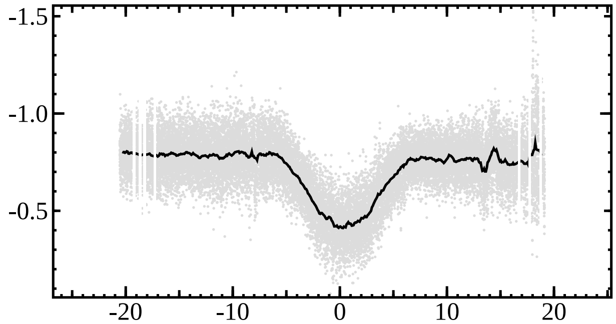

Fig. 6. The lightcurve of phenomenon 1997 09 29 3 OCC 2.

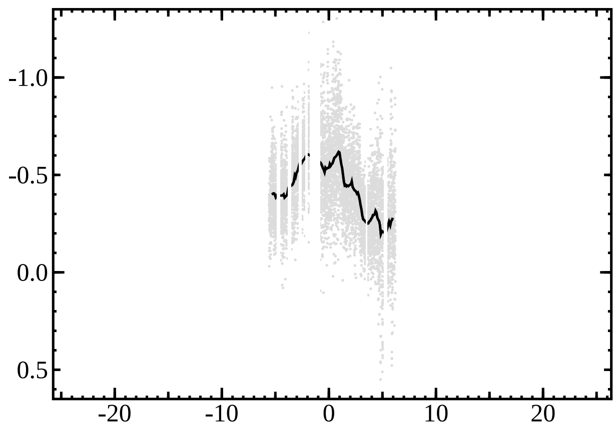

Fig. 7. The lightcurve of phenomenon 1997 10 07 4 OCC 1.

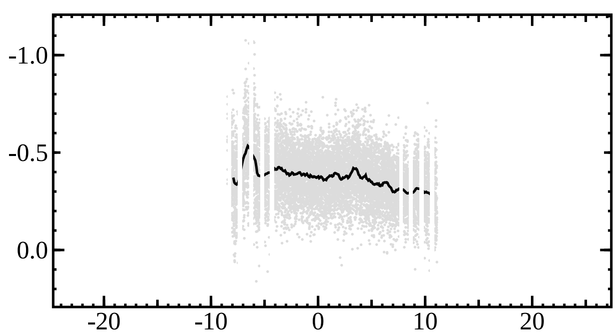

Fig. 8. The lightcurve of phenomenon 1997 10 18 1 OCC 2.

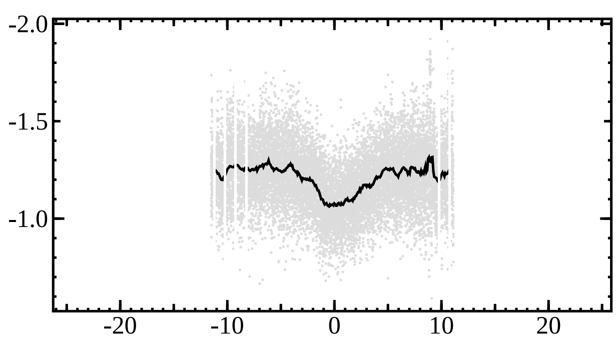

Fig. 9. The lightcurve of phenomenon 1997 11 25 3 OCC 1.

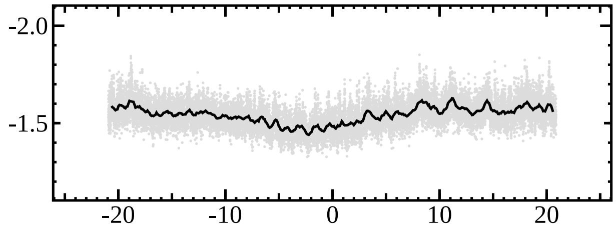

Fig. 10. The lightcurve of phenomenon 2003 01 09 3 OCC 1.

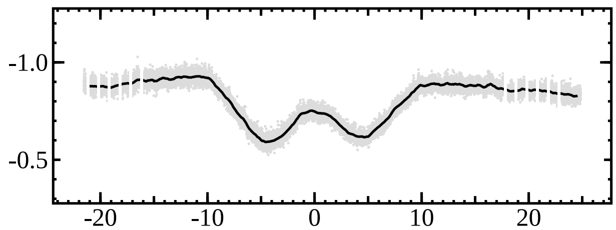

Fig. 11. The lightcurve of phenomenon 2003 02 03 2 OCC 3 and 2 ECL 3.

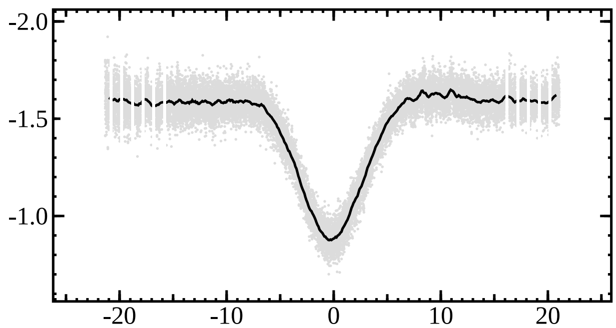

Fig. 12. The lightcurve of phenomenon 2003 02 18 4 ECL 3.

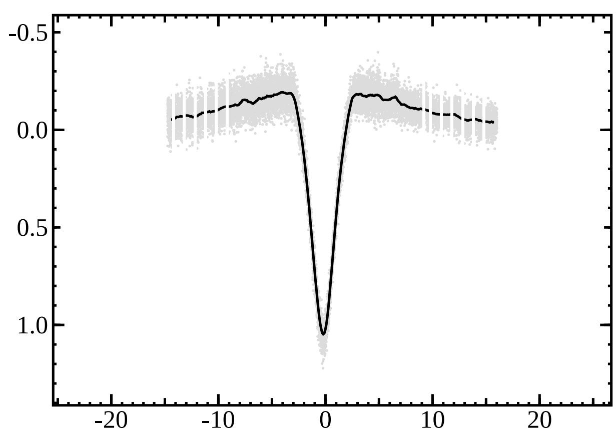

Fig. 13. The lightcurve of phenomenon 2003 02 19 4 OCC 1.

4. Results and Discussion

For the PHEMU97 campaign, a film could be recorded for 12 phenomena, but only for 9 phenomena could a light curve be established. For the other 3 phenomena the satellites disappeared in the clouds.

For the PHEMU03 campaign, we obtained 12 films, covering 14 phenomena (2 of the films contained 2 phenomena). One film could not be reduced because the satellites were too close to Jupiter and could not be separated

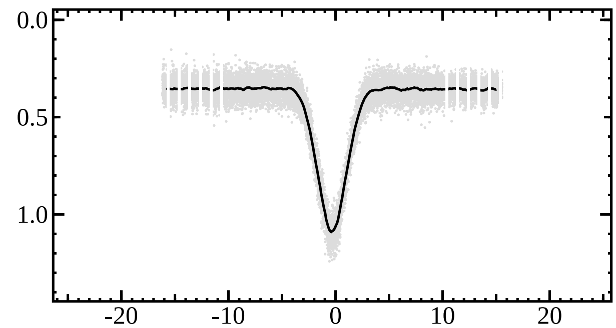

Fig. 14. The lightcurve of phenomenon 2003 02 19 4 ECL 1.

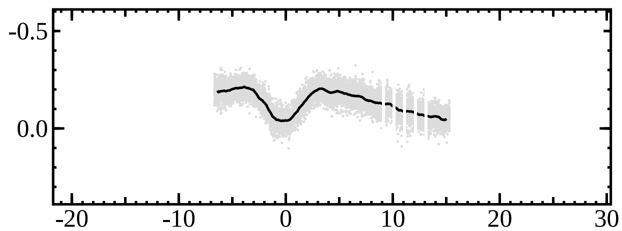

Fig. 15. The lightcurve of phenomenon 2003 02 27 1 OCC 4.

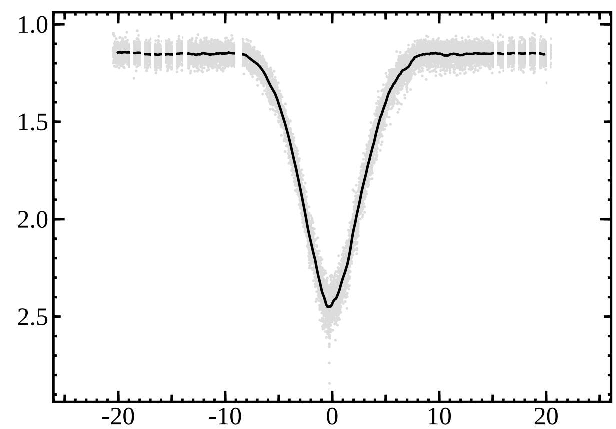

Fig. 16. The lightcurve of phenomenon 2003 03 15 3 ECL 4.

from the glare caused by Jupiter. For one of the phenomena, there were numerous clouds, and only some portions of the light curve contain useful data.

Figures 1 through 20 give the individual light curves of the phenomena. The horizontal scale is the same for each light curve, and is in minutes from the predicted epoch of mid-event. The vertical scale gives the magnitude difference between the satellite and the reference satellite. The figures show the individual data points in grey, and the running average in black. The difference in dispersion between the PHEMU97 and PHEMU03 campaigns is striking, and is due to the difference in altitude of Jupiter in the sky, which is in turn caused by its difference in declination: −18 deg in 1997 and +18 deg in 2004.

Table 1 lists the phenomena that we attempted to observe. The first three columns give the necessary data for identifying the phenomenon observed: date, nature of the phenomenon (‘OCC’ standing for ‘occults’ and ‘ECL’ for ‘eclipses’, and 1, 2, 3 and 4 for Io, Europa, Ganymede and Callisto, respectively) and epoch of mid-event in TT, as announced by the IMCCE (ftp://ftp.bdl.fr/pub/ephem/satel/phemu03/phemu03liste_eng.txt). The fourth column lists the observers, with the codes TP = Thierry Pauwels, JC = Jan Cuypers, PV = Piërre Vingerhoets, PL = Patricia Lampens.

The next columns summarise the results obtained. The fifth column gives the file name used for the table as available from the CDS. Identical file names means that one light curve contains two phenomena. The sixth

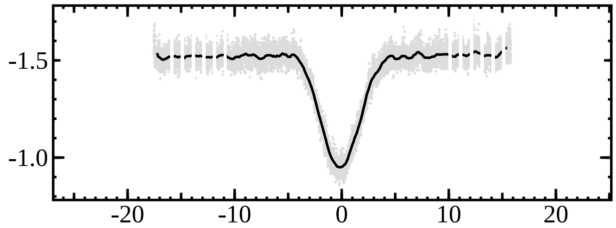

Fig. 17. The lightcurve of phenomenon 2003 03 18 2 ECL 3.

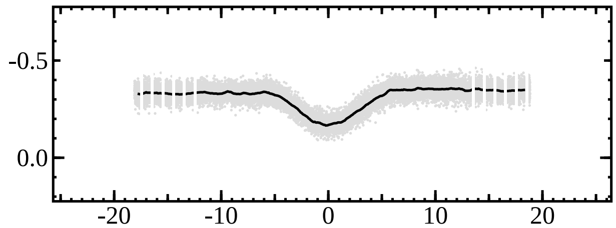

Fig. 18. The lightcurve of phenomenon 2003 03 24 1 ECL 3.

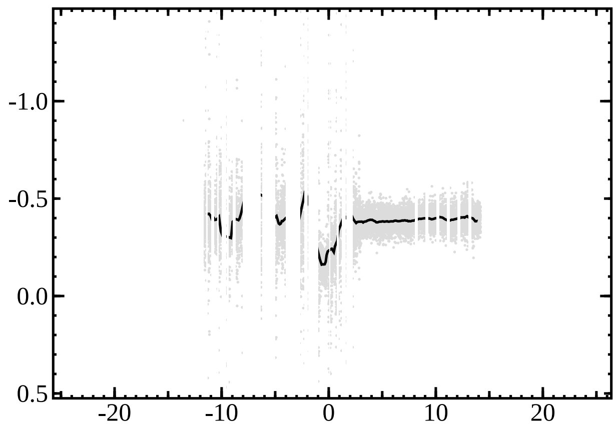

Fig. 19. The lightcurve of phenomenon 2003 03 26 2 ECL 1.

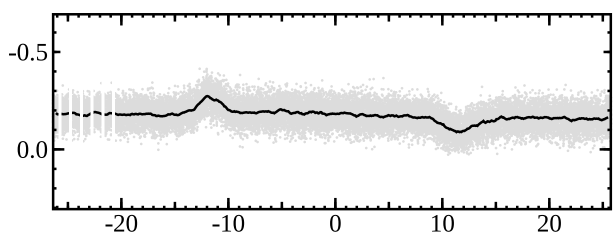

Fig. 20. The lightcurve of phenomenon 2003 04 11 3 ECL 2 and 4 ECL 1.

column mentions whether we used the methane band filter, the seventh column the degree in x used for modelling the sky background. Column 8 gives the satellite (in the case of an eclipse) or the satellite combination (in the case of an occultation, where during the greatest part of the phenomenon the satellites could not be separated) that we monitored, and column 9 the reference object, with the codes I, II, III and IV for Io, Europa, Ganymede and Callisto, the last column gives the assessment of the sky quality by the observer.

Table 2 gives notes for individual phenomena.

The detailed tables with data, one for each phenomenon, are available at the CDS and contain the following information. File names correspond to the codes given in the fifth column of Table 1. Column 1 gives the image sequence number. Missing numbers correspond to gaps in the light curve. Column 2 gives the Julian date of the

Table 1. The list of phenomena.

date	phenom.	TT-mid predicted	observers	file name	filter used?	deg mod	sat obs	reference	sky
					PHEMU97				
1997 09 18	1 ECL 3	19:35:55	TP,PV					*no lightcurve: clouds*	
1997 09 19	4 OCC 3	22:15:50	TP,JC,PV	79j.dat	no	3	III+IV	PPM 238231	cirrus + cirrocumulus
1997 09 21	3 ECL 1	20:32:14	TP,JC,PV	79l.dat	yes	1	I	IV	light cirrus
1997 09 22	3 ECL 2	19:02:59	TP,PV	79m.dat	yes	1	II	III	twilight
1997 09 25	1 OCC 3	19:55:28	TP,PV	79p1.dat	yes	2	I+III	II	reasonable
1997 09 25	1 ECL 3	22:33:38	TP,PV	79p2.dat	yes	1	III	I	reasonable
1997 09 28	3 OCC 1	20:53:34	TP,JC					*no lightcurve: clouds*	
1997 09 29	3 OCC 2	18:43:22	TP,PV	79t1.dat	no	2	II+III	I	altocumulus + cirrocumulus
1997 09 29	3 ECL 2	22:47:27	TP,PV					*no lightcurve: clouds*	
1997 10 06	3 OCC 2	22:13:33	TP,PV					*no lightcurve: rain*	
1997 10 07	4 OCC 1	19:36:46	JC,PV	7a7.dat	yes	1	I+IV	III	clouds
1997 10 18	1 OCC 2	18:23:25	TP,JC	7ai.dat	yes	1	I+II	III	reasonable
1997 10 23	2 OCC 3	20:44:01	JC,PV					*no lightcurve: clouds*	
1997 10 25	1 OCC 2	20:44:14	JC,PV					*no lightcurve: technical problems*	
1997 11 18	3 OCC 2	19:10:11	TP,JC,PV					*no lightcurve: clouds*	
1997 11 18	3 ECL 1	19:18:48	TP,JC,PV					*no lightcurve: clouds*	
1997 11 25	3 OCC 1	18:40:22	TP,JC,PV	7bp.dat	no	3	I+III	II	cirrocumulus + altocumulus
					PHEMU03				
2003 01 09	3 OCC 1	00:44:29	TP,PV	d18.dat	yes	1	I+III	II	clear sky
2003 02 03	2 OCC 3	23:31:56	TP	d23.dat	yes	1	II+III	I	clear sky
2003 02 03	2 ECL 3	23:40:40	TP	d23.dat	yes	1	II+III	I	clear sky
2003 02 17	1 OCC 2	02:51:24	TP,PV					*no lightcurve: too close to Jupiter*	
2003 02 18	4 ECL 3	20:49:53	TP,PV,JC	d2i.dat	yes	1	III	IV	clear sky with moon
2003 02 19	4 OCC 1	20:32:20	TP,PV,JC	d2j1.dat	yes	1	I+IV	III	clear sky
2003 02 19	4 ECL 1	22:16:46	TP,PV,JC	d2j2.dat	yes	1	I	III	clear sky
2003 02 27	1 OCC 4	22:04:00	JC,PV	d2r.dat	yes	1	I+IV	III	cirrus and clouds
2003 03 15	3 ECL 4	22:15:53	JC,PV	d3f.dat	yes	1	IV	III	clear sky
2003 03 18	2 ECL 3	20:47:57	JC,PV	d3i.dat	yes	1	III	IV	bad seeing—maybe some haze
2003 03 24	1 ECL 3	22:02:36	TP,PV	d3o.dat	yes	1	III	I	*(not recorded)*
2003 03 26	2 ECL 1	20:42:00	TP,PV	d3q.dat	yes	1	I	II	passing clouds
2003 04 02	2 ECL 1	22:59:05	TP,PV					*no lightcurve: clouds*	
2003 04 11	3 ECL 2	21:03:03	TP,PL	d4b.dat	yes	1	II	I	thick cirrus + moon 1st quarter
2003 04 11	4 ECL 1	21:26:45	TP,PL	d4b.dat	yes	1	I	II	thick cirrus + moon 1st quarter

epoch. Columns 3 and 4 give the magnitude of both monitored objects (the satellite involved in the phenomenon and the reference object), with an arbitrary offset, which is variable because of its dependence on the atmospheric transparency. The last column gives the magnitude difference between the programme satellite and the reference object. Usually this is the reference object minus the programme satellite, but there are a few exceptions.

It is puzzling that for occulations the light curve invariably increases before the phenomenon, and decreases again afterwards. There is no such behaviour for eclipses, where the light curve is flat outside the phenomenon. At first we thought this was due to the satellites moving apart and thus filling a larger box after the phenomenon while the aperture of the ‘aperture photometry’ remained constant, causing an increasing part of the light to fall outside the box. However, in the second version of the reduction, where the pixels containing a satellite image were

Table 2. Individual notes on phenomena.

1997 09 19	4 OCC 3	Due to the large distance between the monitored phenomenon and the reference object there are some sudden jumps in the light curve that are probably due to clouds.
1997 09 25	1 OCC 3	For part of the observation the sky background could not be modeled. This part of the light curve has been removed. There is no obvious explanation for the rise of the light curve in the beginning and the subsequent decrease. The difference between the satellites involved in the phenomenon and the reference satellite is one magnitude larger than expected.
1997 09 25	1 ECL 3	Very bad seeing.
1997 09 29	3 OCC 2	For several parts of the observation the sky background could not be modeled. These parts of the light curve have been removed.
1997 10 07	4 OCC 1	Due to clouds the timing of the phenomenon is lost after 19:41:52. Around 19:34:44 and 19:39:14 due to clouds the satellites almost disappeared. The most problematic periods were removed from the light curve. Very variable transparency of the sky.
1997 11 25	3 OCC 1	Jupiter and the satellites remained in a hole between the clouds, until they disappeared at 18:46.
2003 01 09	3 OCC 1	The proximity of Jupiter caused some blooming on some of the images. There is an unexplained quasi-periodicity in the light curve (period ~ 1.2 minutes). The flashing mechanism did not work, therefore timings were recorded by hand with the ticking procedure.
2003 02 03	2 OCC 3 and 2 ECL 3	One light curve for two phenomena. Both phenomena overlap.
2003 02 27	1 OCC 4	Flashes were generated only after the phenomenon, such that timings are extrapolations rather than interpolations. However, the error in the timings should be no larger than 0.2 seconds.
2003 03 15	3 ECL 4	Part of the light curve had to be removed because the satellite moved too close to the border of the window. Slower acquisition rate.
2003 03 18	2 ECL 3	Bad focus, probably does not affect the light curve. Slower acquisition rate.
2003 03 26	2 ECL 1	Large parts of phenomenon lost in clouds. Timings may be systematically off by 0.1 second, because the first image of each object was not visible.
2003 04 11	3 ECL 2 and 4 ECL 1	Two phenomena in one light curve. The satellite involved in the second phenomenon was used as reference for the first phenomenon and vice versa.

determined automatically (such that the ‘size of the aperture’ was adapted automatically), the phenomenon is still as prominent. We have no explanation for this phenomenon.

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