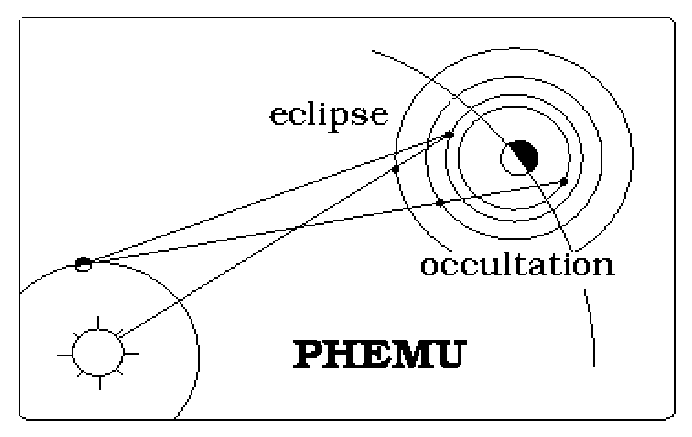
Institut de mécanique céleste et de calcul des éphémérides
77 avenue Denfert-Rochereau, F-75014 Paris, France
Observatoire de Paris - CNRS



Technical Note n°3
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THE PHOTOMETRIC OBSERVATION OF THE MUTUAL EVENTS

J.-E. Arlot (a), J., Lecacheux (b)
(a) Institut de mécanique céleste, UMR 8028 du CNRS, 77 avenue Denfert-Rochereau, F-75014 Paris
(b) LESIA,Observatoire de Paris-Meudon, place J. Janssen, F-92190 Meudon

I - Introduction

Before observing the events during an opportunity which is very short, it seems to be necessary to remind the observers to be very careful and to follow a very strict procedure for the photometric observation of the mutual events either with a photoelectric photometer or with a CCD receptor. A technical help in the use of photoelectric photometers or CCD targets will be provided in a next note. The present note would like to state the principles which will lead to useful observations : what to observe, when to observe and how to observe. These observations are easy to make and they are spectacular because of the large magnitude drop to be observed and because of the fastness of these events. The help of previous campaigns of observations will provide us what we need to succeed in the future observations.

II - The time-scale for the observations

Since these observations are made in order to improve the dynamical models of motion of the objects themselves, all the data must be referred to a well known time-scale to the nearest tenth of a second of time in order to be able to link all the observations together. In fact, all the observational data should be referred to UTC (Universal Time). Internal clocks of computers are not confident because not linked continuously to UTC. If it is not possible to be connected to UTC any time, it is necessary to verify the used clock before and after the observation and to record the difference between the used clock and UTC at that time (never modify the clock during an observation). The sidereal time must never be used in the present work. We learned, through the past experiences that this calibration of the time-scale should never be made after the observation since anything can happen such as a failure of the hardware. Unfortunately, all the observatories do not have a sure clock related to UTC and the best to do is to note the difference of the available time-scale with UTC before and after the observation by calling UTC through the phone network or thanks to a radio-receiver in order to know if a drift occurs in the time-scale. The time accuracy should be better than 0.1 second of time that is to say that each photometric measurement of the recorded light-curve must be dated in UTC with an accuracy better than 0.1 second of time. Note that the satellite Io, for example, has a velocity of 17.2 km/s, so that an accuracy of 0.1 second of time

corresponds to an accuracy of 1.7 km in space. Since the internal accuracy of the theory of motion of the satellites is around one kilometer, anyone may understand that an accuracy better than 0.1 second of time is necessary. Note that the time obtained by GPS is confident.
At last, be careful to start the observation well in advance. The predictions are not so precise and the events could start a few minutes before the predicted time. The long events may begin 10 minutes or more before (or after) the predicted time. Don't forget that predictions are often made in Terrestrial Time which differs from the UTC of about one minute of time (TT - UTC ~ 66 seconds in 2009).

III- Choosing the events

If you are able to observe only a few events, what events should you choose ? For that, you may follow the following rules:
- choose events when Jupiter is not too low above the horizon and avoid events during twilight, except if you use a CCD and if you are able to record a reference satellite present in the field;
- avoid grazing events and events the magnitude drop of which is less than 10 p. cent; the best events to observe are those the magnitude of which is larger than 20 p. cent and smaller than 90 p. cent;
- choose events occurring at more than 3 jovian radii to Jupiter;
- prefer the occultations to the eclipses and choose the eclipses where the eclipsing satellite is far from the eclipsed one ;

- prefer the events involving satellite 4, Callisto
- avoid the too long events if you are not able to observe the entire light curve (Jupiter mat be below the horizon at the end of the event...).

Of course it is better to try to observe the maximum of events.

IV - The receptors to be used

The goal is to record the variation of a light signal and to make a photometric measurement depending on the time with a high frequency of acquisition (from 0.5 to 5 points per second of time). For that, several receptors may be used from the more simple recording only one signal to the more elaborated recording simultaneously several signal in several wavelengths. These receptors are:
- single channel photometer ;
- spectral multichannel photometer ;
- spatial multichannel photometer ;
- spectrophotometer ;
- two-dimensional receptor (CCD, video).

We will not provide information on the receptors themselves (other technical notes will be dedicated to the receptors), but only on the problems related to the photometric recording of the events, the wavelengths to be used, the sampling integrated time and the making of the observation.

<u>a) the wavelength</u>

The spectral band where the observation will be made depends on several factors : first you have to choose the wavelength where the receptor used is the more efficient; second you may choose a wavelength in which the observation will provide the most interesting information. Note that any wavelength is interesting but we may see what wavelengths are more favorable to reach new information:

- case of a receptor working in only one wavelength : any visible wavelength will provide useful lightcurves. The V, R and I bands are more efficient, but with a photoelectric photometer you probably will have no choice. Note that it is possible to decrease the light from Jupiter (for events occurring very near the limb of the planet) by using interferential filters such as CH_4, (7260 A, 8300 A,...) even it is efficient only very near the planet: two-dimensional photometry is more efficient. For observations to be made in a city polluted by light, the 5000 to 5300 A spectral band should be of any interest as shown by the following diagram showing the brightness of the urban sky depending on the wavelength.

- case of a spectral multichannel photometer : if the receptor allows to record the event in several wavelengths, please do it: recording several lightcurves of the same event from the same telescope is highly interesting: it is the only way to decorrelate local photometric accidents depending on the site and on the observational conditions from interesting information on the grounds of the satellites. As said previously, all the wavelengths are interesting because of the few experience we have on such simultaneous lightcurves.

-case of a two-dimentional receptor (CCD or video): observe without filter in the wavelength of sensitivity of the receptor to get more flux, mainly when observing with a small telescope.

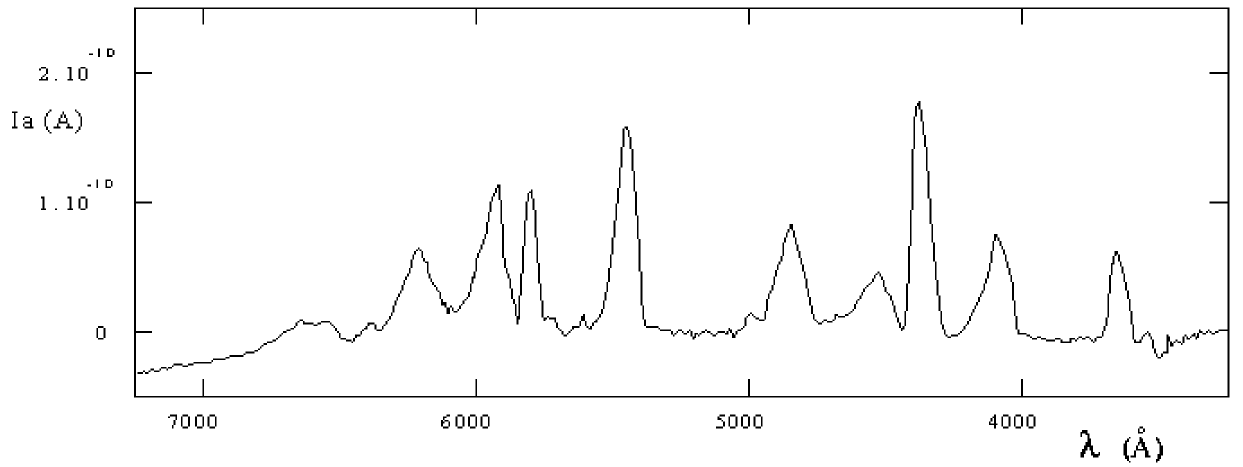


Fig. 1 – Brightness of the sky background versus wavelength (from G. Malinié, thesis Paris VII).

b) integrating time and time sampling

- the integrating time should be not too short (it is necessary to have a sufficient signal/noise ratio) and not too long (since the events are very fast, we need to record enough points to model the light curve). The experience shows that, depending on the receptors, the integrating times vary from 0.1 to 2 seconds of time.
- the time sampling depends on the duration of the event : for long events (about one hour) one point per second or per 2 second is sufficient.

- be careful to take into account the dead time used for the storage of the observation (flux or image) which must be added to the integrating time in order to get the sampling.

Be careful to avoid a saturated image: the photometry will not be confident. The Galilean satellites are very bright and they may saturate the receptor. Several solutions are possible:

- decrease the integrating time (but it will decrease also the signal/noise ratio)
- decrease the aperture of the telescope
- use a density filter to decrease the light arriving on the receptor
- put slightly out of focus the images to spread the light on the detector

The last solution is very easy to perform even at the last moment. Note that the images may appear not saturated before the event but when the two satellites in occultation will be very close to each other, the image could saturate because of the bad seeing which avoided the saturation when the satellites were separated.

c) the diaphragm

The diaphragm is the field, chosen by hardware or software, containing the object(s) the light flux of which is to be measured all along the event. For example, in the case of an eclipsed satellite, this satellite will be included in the diaphragm and its light flux measured during the event. In the case of an occultation, both the occulted and the occulting satellites will be included in the diaphragm and their light flux measured before, during and after the event. Several diaphragms may be useful in order to record references and the sky back ground for calibration. This may be complicated by the presence of another satellite in the vicinity of the involved satellite or by the closeness of the bright planet. Several examples will be shown below. The choice of what will be measured in the diaphragm(s) will provide the quality of the observation.

The diaphragm will be different depending of the receptor used:

-in the case of a two-dimensional CCD receptor recording a series of images, the problem is easier to solve: the diaphragm will be designed by software after the observation when analyzing the images. If the choice is not good, it is possible to do it several times. More, the reference and the sky background, useful for the calibration of the light flux will be measurable on the images at the same time of the satellite(s) implied in the event thanks to several diaphragms.

-in the case of a spatial multi-channel photometer, we should choose carefully the different diaphragms before the observation: one for the implied satellite(s), one for the sky background around the satellite (beware the gradient) and one (or more) for the reference object. Attention to a satellite (or a star !) arriving in a diaphragm during the observation... or to the planet itself (do not forget that the satellites move fastly and that Jupiter, for example, has a magnitude of 5 per square arcsecond).

-in the case of a classical one-channel photometer, we have only one diaphragm during all the observation. We will include in this diaphragm the implied satellite(s) after studying carefully what will occur during the event. The recording of a reference and of the sky back ground will be possible before and after the event for a short event or during the event by moving the telescope to the reference or to the sky back ground for a long event.

In the case of a two-dimensional CCD receptor, a large field is recorded continuously as image. Therefore, it is important to define very well the field of the images before the event to be able to determine efficient diaphragms during the reduction. Be sure that a reference object is available and will not be disturbed during the event by another satellite moving during the event (especially for long events).

The study of the field before each event is now easy thanks to interactive softwares available on www.imcce.fr/sat. Note that in any case a too large diaphragm will include too much light from the sky background leading to a bad signal/noise ratio and that a too small diaphragm will make difficult to catch all the light from the implied satellite in the diaphragm (especially with a bad seeing).

V - The making of the observation

The observation of the Galilean satellites is easy because:

- they are bright (magnitude 5)
- they orbit far (in apparent angular distance) from the bright Jupiter (until 14 arcmin)

The image below shows the Jovian system in a small telescope.

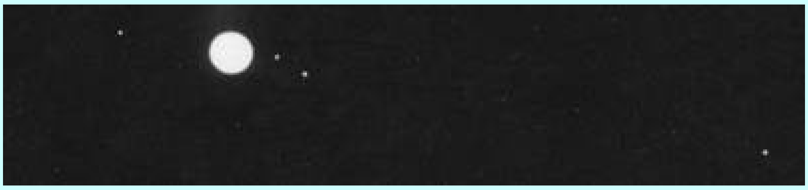


Figure: the Jovian system (field: 20 arcmin)

Even if these observations may seem to be easy, the nights are always too short to make all the preparation to the observation of the events and to allow improvisation : therefore, prepare a written procedure with a well-adapted timing in order to be sure to forget nothing (calibrations, ...).

The observation of the satellites of Saturn is more difficult as shown by the figure below. The magnitude of the satellites are from 8 to 14.

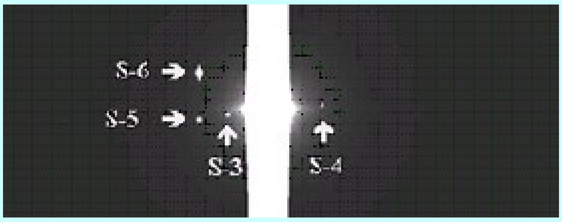
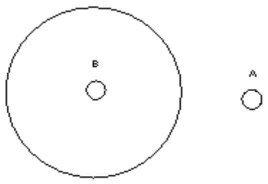


Figure: the Saturnian system (field: 10 arcmin)

In spite of the difficulty and of the need of a larger telescope, the principles are the same as for the Galilean satellites.

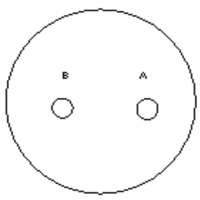
<u>a) the preparation</u>

Even we are doing relative photometry, the photometric calibration using quasi-solar type stars may be interesting. During the event, another satellite will be used as the photometric reference. This choice has to be made well in advance to the event. Be careful to identify correctly the satellites, especially if you use optical mounting reversing the field. If you used a one-channel photometer or a multi-channel photometer, you must choose the diaphragm before the observation. Several cases may occur as shown below for the recording of the concerned satellite.



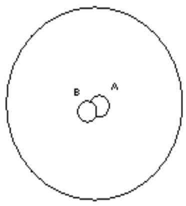
Example 1 :

A eclipses B, A far from B during all the event : B will be measured alone.



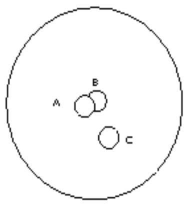
Example 2 :

A eclipses B, but A and B are very close. A and B should be measured together. However, before or after the event, it will be necessary to measure separately the flux of A and B. In some case, it will be necessary to wait in order to have a sufficient separation between A and B.



Example 3 :

A occults B. A and B will be recorded together but they should be measured separately as indicated above.



Example 4 :

A occults B, and C approaches A and B during the event. A, B and C will be recorded together but we will measured A, B and C separately after or before the event as indicated above.

Be careful to know in advance the relative motion of the satellites in order to be sure that none of the satellites will leave the diaphragm during the recording of the event (especially during long events). Note that the magnitudes of the satellites are not well-known especially in nonstandard spectral band and that these magnitudes vary depending on the orbital positions of the satellites, so that it is necessary to measure the individual light flux of the satellites before and after the event.

Start the recording of the event well in advance : for long events, an error of 10 minutes of time in the timing is possible.
Be careful to the positions of Jupiter in the sky. The observation is possible even very low on the horizon (less than 10 degrees) but not if Jupiter is behind a mountain or behind a building. Therefore, calculate the local positions of Jupiter before the event.

Polluting light and absorption : only the light from the Moon or from Jupiter may be predicted. For the Moon the use of a R or I filter will solve easily the problem. For the light from Jupiter, a narrow filter `` CH4 `` may be interesting as indicated above. The sky background has a high gradient near Jupiter and its measurement should be made very carefully. The next figure suggests a way to measure this sky background : measure it symmetrically from Jupiter. . Another way is to model the sky background with a two or three degrees polynomial fitted on the images without all the objects but this method is possible only on recorded CCD images.

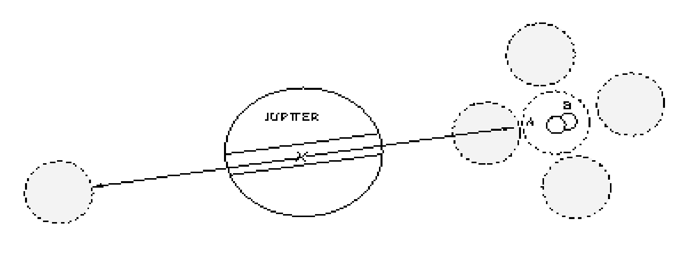


Fig. 2 – Sky background is to be measured in the dashed areas.

The absorption is harmful if it varies during the events (small clouds): the only solution is the use of a two-dimensional receptors or the simultaneous recording of a reference object. Same if the sky background varies (twilight) the use of a twodimensional receptor is recommended.

b) The recording of the event

The measurement of the sky background is necessary in all cases, even if there is no light pollution. In the case of a single channel photometer, this measurement should be made before and after the recording of the event in the case of a short event (less than 20 minutes) and once every 5 minutes in the other cases. The method described in the previous paragraph is applicable for the events near Jupiter: four measures around the implied satellites. If necessary only one measure above and one below will be sufficient. The use of a multi-spatial channel photometer or of a two-dimensional receptor avoid the previous measures.

The atmospheric absorption leads to a magnitude drop proportional to the zenithal distance (air mass) as determined by the ``droite de Bouguer". The chapter “Refraction” provides the principles of this mechanism. However one should be careful with the given values (0,165 magn., 0,29 magn., 0,59 magn.) which correspond only to mean values for a given site. In fact the absorption may vary considerably from one night to another ; they may vary also during the same night. Therefore the ``droite de Bouguer" will be no more a ``droite": the points scatter, mainly near the horizon. This, to show that it may be useful to make differential measurements referred to another Galilean satellite or to a standard photometric star whose spectral type is quasi-solar.

c) observations to be made cautiously

- Observations made low on the horizon: in that case, be careful with the refraction which increases rapidly and which needs to correct the guiding of the telescope. Be also careful with the absorption which increases and may also vary. The measurement of a reference object is highly necessary simultaneously (CCD two-dimensional detector) or from time to time (single channel photometer). The light curve obtained with a single-channel photometer is shown in fig. 4. The reference object and the sky back ground have been recorded during the event. Note that in any case, the best is the used of a two-dimensional receptor CCD allowing to measure simultaneously all the interesting objects (and the sky background).

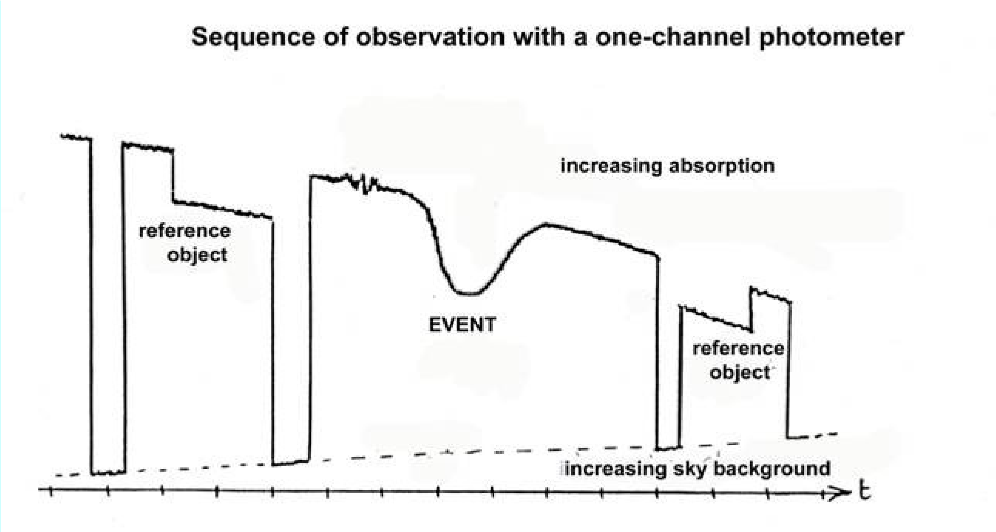


Fig. n°4

- Observations made during twilight: they are confident if some precautions have been taken. Do not forget that the brightness of the sky doubles every 4 minutes before sunrise. Observing in the R or I band will allow to observe latter in the twilight and sometimes during daylight if Jupiter is far from the Sun. Observing in daylight is possible but difficult because of the very bad seeing as soon as the Sun is risen. The infra red CH4 or K-band filter allows also the observations in daylight. Light curves will have the shape shown in fig. 5. In the case of an infrared photometer, the sky background is generally subtracted in real time using a 30Hz or 60 Hz oscillating modulator. Observations may be made during daylight if the problem of the guiding of the telescope is solved. The measurement of a reference object is also necessary in that type of observation. In the section "Examples of light curves" an example is provided showing an observation during twilight and through light clouds.

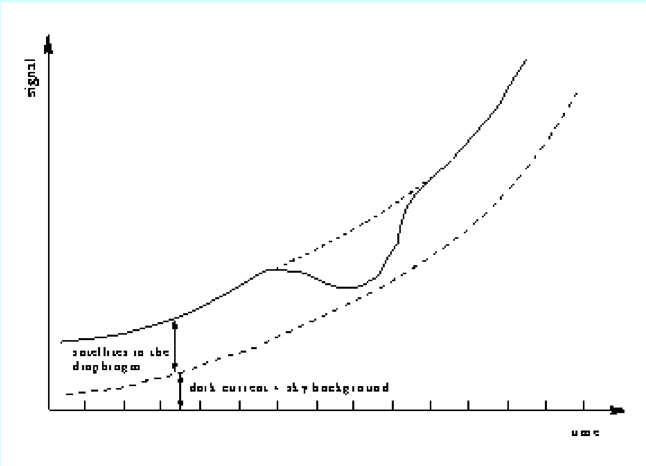


Fig. 5 (a) - Lightcurve

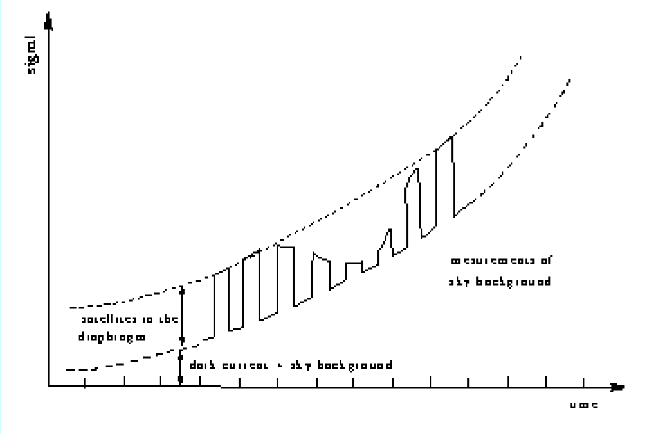


Fig. 5 (b) - rough measurements

d) the light curves to be obtained

The light curves obtained depend on the way the observation has been made and on the objects included in the diaphragm. What kind of light curves will we get ? The figure 3(a) shows the case of an occultation or an eclipse for which two satellites (or more) are included in the diaphragm (the light flux drop may never reach zero). The figure 3(b) shows the case of an eclipse for which only the eclipsed satellite is included in the diaphragm. Note that the light curves are not always symmetrical. The phase defect, the features on the surfaces and the light scattering may modify the shape of the light curves compared to what will happen with satellites the surfaces of which are uniform.

The light curves as shown on fig. 3 have been calibrated thanks to the reference object and the sky back ground: raw light curves may have any shape as shown by fig. 4 and 5.

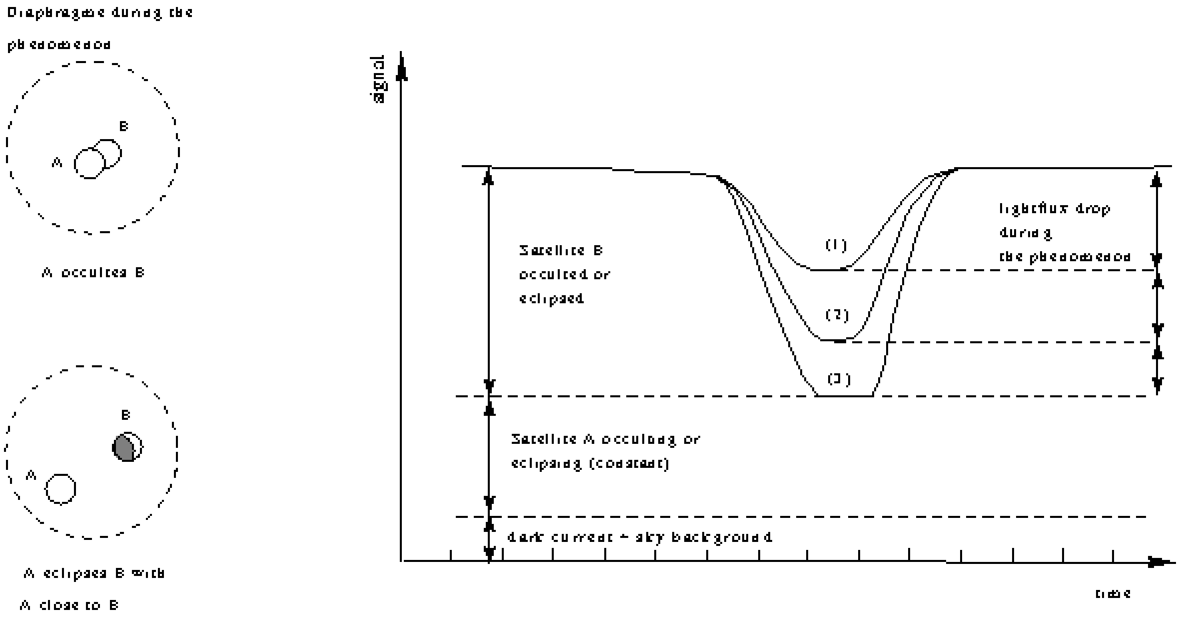


Fig. 3 (a) – occultation or eclipse where the satellites are both in the diaphragm
(1): partial phenomenon
(2): annular phenomenon (the minimum theoretically shows a plateau)
(3): total phenomenon (a plateau appears when the phenomenon is total)

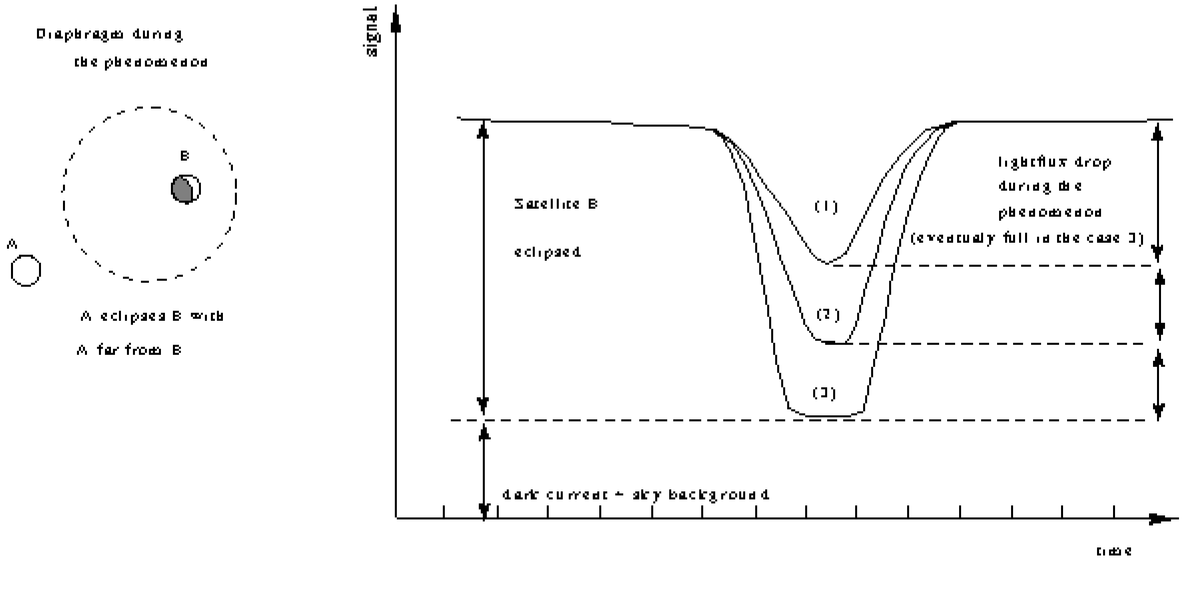


Fig. 3 (b) – eclipse where the eclipsed satellite is alone in the diaphragm
(1): partial phenomenon
(2): annular phenomenon (the minimum theoretically shows a plateau)
(3): total phenomenon (a plateau appears when the phenomenon is total)

e) let's remind the errors to be avoided

- to mix satellites (confusing North/South or East/West...);

- to start observing to late and to have not enough time for the calibrations;

- to miss observations thinking that Jupiter is too low on the horizon: observations are possible at 10 degrees above the horizon, even less…;

- to choose a wrong diaphragm (when chosen by hardware) and to need to change it during the event or a wrong field in case of use of CCD;;

- to suppose that the motion of the satellites is linear and uniform;

- to think that we know everything on the Galilean satellites (the magnitude may change from one point to another on the orbits;

- to have a wrong time scale and to be not sure of the clock (be sure to have the UTC available);

In brief, prepare carefully the observation and follow minute after minute a procedure written in advance with a precise timing

VI - Summary of the most important points to be examined before the observation

1 - be sure to have a time scale in UTC accurate to 0.1 second of time ;
2 - verify that Jupiter and the satellites will be visible during all the observation ;
3 - verify that each point of the lightcurve is correctly referred to the time scale with an accuracy better than 0.1 second ;
4 - think to use the right filter : 5000-5300 A, in an urban polluted site, R or I filter during twilight or near the Moon, but, if possible use a filter designed for the receptor that you use ;
5 - if you are not familiar with the material that you use, take a little more time before the observations to know it
6 - be sure of the identification of the satellites (beware the optical mounting which reverse the field) ;
7 - determine precisely the field to be recorded (CCD) or the size of the diaphragm (photometer) and what satellites should be in the diaphragm during all the time of the observation (especially for long events) ;
8 - know precisely the motions of the satellites during the events and take into account the refraction when observing low on the horizon ;
9 - take into account the presence of the Moon or of Jupiter to prepare the observation ;
10 - make individual photometric measurements of the satellites before and after the observation ;
11 - measure the sky background in different areas several times during the observation ;
12 - measure the atmospheric absorption thanks to a reference object ;
13 - be careful for the observations during twilight for which a special procedure is necessary.
14 – try to observe an eclipse by the planet Jupiter before starting the observation of the mutual events to be familiar to the material and the procedure which may be improved.

VII - Conclusion

Following all these recommendations, the observation of a mutual event should be useful. Don't forget that many observations were useless in the past because of wrong time scale, saturation of the images, etc... A next technical note will explain how to reduce the observation and to get a light curve useful for analysis.

ANNEX . Translation of **"Introduction à l'Astrophysique: les étoiles" de J. Dufay**

Variations of absorption as a function of the zenith distance: the Bouguer's method

If we suppose that the atmosphere depends only upon the altitude, it may be taken as a succession of thin layers, concentric to the Earth, each one having a well-defined absorption coefficient.

For a zenital distance less than 60 or 65°, we may neglect the refraction (< 2') and the curve of the Earth. The light rays, rectilinear, cross a series of layers plane-parallel (fig. 2). Across a layer of thickness dz, characterized by its absorption coefficient a, the trajectory of a ray of light coming from a star at zenital distance ζ has $dz \sec \zeta$ as length and the corresponding optical density is:

$$dD = a \, dz \sec \zeta$$

The total optical density of the atmosphere at a zenital distance ζ is the sum of the elementary optical densities of the successive layers.

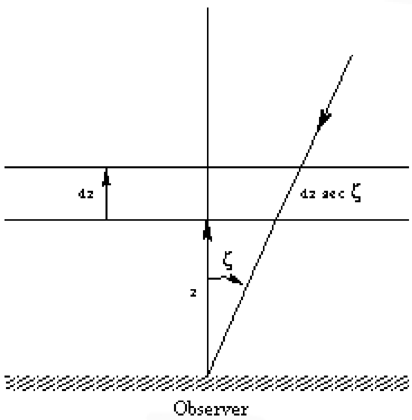


Fig. 2.

$$D(\zeta) = \sec \zeta \int_{z_0}^{\infty} a \, dz.$$

the integration may be extended from the ground (altitude z_0) until the infinite, but the absorption coefficient a becomes zero at the upper limit of the atmosphere. This integration represents obviously the optical density $D(0)$ at the zenith of the observing site and we may write:

$$D(\zeta) = D(0) \sec \zeta.$$

In order to evaluate the optical density at a zenital distance ζ less than 65°, it is not useful to know the law of variation of the absorption coefficient a as a function of the altitude. It is sufficient to know the optical density at the zenith and the relationship above allows to determine this density thanks to the observation.

By replacing $D(\zeta)$ by $\log (Eo / E)$ we have:

$$(5, 1) \qquad \log E = \log E_0 - D(0) \sec \zeta.$$

The logarithm of the illumination received on the ground is a linear function of $\sec \zeta$. From this, the "Bouguer method":
We follow the variations of the illumination E when the star drops or rises on the horizon and we build a plot with $\sec \zeta$ in abscissa and $\log E$ in ordinate. The points will be near a line whose slope is D(0) and the ordinate at the origin is the logarithm of the illumination Eo above the atmosphere. We may put the magnitudes in ordinates in place of the logarithm of the illuminations (fig. 3). The equation of the line is:

$$(5, 2) \qquad m = m_0 + \Delta m_0 \sec \zeta.$$

its slope $\Delta mo = - 2.5 \, D(0)$ is the magnitude drop at the zenith and its ordinate at the origin mo, the magnitude above the atmosphere.

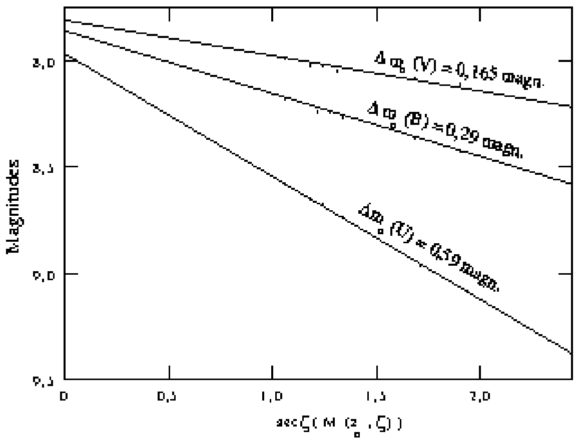


Fig. 3. – variations of the magnitude of a star in yellow (V), (B) and ultraviolet (U), as a function of the air mass (photo electric measurements of J.H. Bigay). *The lines were shifted vertically of arbitrary quantities; magnitudes apart of the atmosphere: V = 8.77, B = 9.94, U = 10.75 (K0 spectrum).*

So that the coefficient of absorption a has a defined value, measurements must be made in roughly monochromatic light. Used on a too large spectrum, the Bouguer's method would not have any sense. It supposes that the laminated layers remain stable during the measurements, i.e. a few hours. This condition is not always satisfied even with clear sky and it may appear that the method is not applicable in some cases.

When the zenith distance is larger than 65°, we may no more neglect neither the curve of the Earth, nor the refraction. We have to take into account layers limited by concentric spheres. The optical density of an elementary layer depends upon its altitude and its thickness. We will consider here that the absorption occurs in all the mass of the atmosphere. The coefficient of absorption is then proportional, at each altitude, to the specific mass. If δ_z is the *relative* density of gas at altitude z referred to gas in normal conditions and a_0 the coefficient of absorption in these conditions, we have:

$$a = \delta_z \, a_0$$

and the optical density at zenith distance ζ is:

$$D(\zeta) = a_0 \int_{z_0}^{\infty} \delta_z \, ds,$$

the integral being taken along the curvilinear ray which crosses the atmosphere until the altitude z_0 of the observer. Following the vertical, the optical density is:

$$D(0) = a_0 \int_{z_0}^{\infty} \delta_z \, dz.$$

Then, we have:

$$\frac{D(\zeta)}{D(0)} = \frac{\int_{z_0}^{\infty} \delta_z \frac{ds}{dz}}{\int_{z_0}^{\infty} \delta_z} = M(z_0, \zeta).$$

The quantity $M(z_0, \zeta)$ is the *air mass* relative to the zenith distance ζ and at altitude z_0. The air mass is evaluated from sounding balloons providing data on temperature and pressure depending on altitude (Link's tables). Bouguer's method may be applied to zenith distances larger than 65° by putting $M(z_0, \zeta)$ in abscissa in place of sec ζ.