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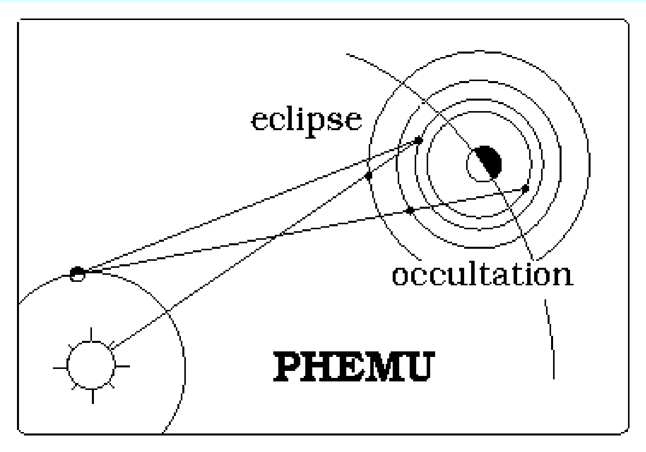

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PRESENTATION OF THE GALILEAN SATELLITES OF JUPITER AND OF THEIR MUTUAL PHENOMENA

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I - **INTRODUCTION**

Galilean Satellites are well-known by the observers: they have been always interesting for astronomers, and much more since they are a goal for space probes. These fast-rotating satellites have their motions perturbated by the Sun, the flatness of Jupiter, their interactions and also by the planet Saturn. These characteristics made that they look like a small solar system where small effects, not yet taken into account, are possible to put into evidence. You will find here after, numerical values of the jovian system, the distance to the Earth of which being between 4.2 and 6.2 A.U. i.e. 0.63 to 0.93 10^{9}km.

	Radii	Orbital period	Semi-major axis		Visual magnitude at opposition	Geometric albedoes (Harris, 1961)				
	km	day	AU	apparent geocen. at opposition		U	B	V	R	I
I	1840	1.76986	0.002820	2′17″	4.8	0.19	0.56	0.92	1.12	1.15
II	1552	3.55409	0.004486	3′40″	5.2	0.47	0.67	0.83	0.93	0.95
III	2650	7.16639	0.007155	5′48″	4.5	0.29	0.41	0.49	0.56	0.57
IV	2420	16.75355	0.012586	10′13″	5.5	0.14	0.21	0.26	0.30	0.31

II - **HISTORICAL**

1. The discovery

At the beginning of the use of the recently discovered refracting telescope, Galileo, observing Jupiter on January 7, 1610, noticed three stars, the motions of which being not explained by the one of the planet (a) . On January 11, Galileo understood that these three stars were orbiting around Jupiter and, on January 13, he saw four such stars. During the year 1610, other astronomers observed these bodies: S.Mayer (who said that he saw them in November, 1609...), Kepler, Harriot, Peiresc,... The identification of the satellites, that is to say the determination of their periods, was made only at the beginning of 1611. An observation of an eclipse (reappearance of J2) was made by Galileo on January 12, 1610, but he understood its meaning only in 1612. It is only in 1643 that an observation of the shadow of a satellite on the disc of Jupiter was made (by Fontana) and in 1693 that a mutual event was observed (by Arnoldt: occultation of J2 by J3).

The use is to designate the Galilean satellites by the roman digits I, II, III and IV beginning by the one the closest to the planet. They are also noted J1, J2, J3 and J4. Their names ``Io, Europa, Ganymede and Callisto" appeared in ``Mundus Jovialis" of S. Mayer (or Marius) published in 1614. Other names were given to the 4 satellites by Hodierna: ``Principharus, Victipharus, Cosmipharus and Ferdinandipharus". Galileo named them ``Medicea Sidera" (i.e. Stars of Medicis), Hevelius:``Circulatores Jovis" or ``Jovis Comites" and Ozanam:``Guards" or ``Satellites" (b).

(a) In this connection, one may read the ``Sidereus Nuncius" of Galileo, published in 1610, in its recent english translation ``The Sidereal Messenger" (Dansons of Pall Mall, London).
(b) Satellite, from latin ``satelles, satellitis": escort.

2. The studies made

The study of the motions of the Galilean satellites began by the time of the first observations. By March 1610, Galileo established that their motions are circular around Jupiter. The first tables of their motions (periods have to be known and an origin for the longitudes must be choosen) were built by Galileo in 1612 and by S. Mayer in 1614. In his tables published in 1656, Hodierna knew the latitudes of the satellites and made predictions of the eclipses. In 1668, J.D. Cassini published his ``tables of the motion and of the calculation of the eclipses". Built on a large number of eclipses, these tables were better than the previous ones. They were improved in 1693 (note that in 1675, Roëmer put into evidence the velocity of light thanks to his observations of eclipses of J1).
In 1719, Pound published similar tables to the ones of Cassini for the calculation of the eclipses, but shortened. In 1749 were published the tables (existing from 1718) of Bradley, made from his own observations. Bradley noticed the inegality of 437 days in the dates of the eclipses of the first three satellites. At the same time, Maraldi pointed out the interactions of the satellites, and eccentricities, as well as the nature of the inequalities, were suspected. In 1741, Wargentin published tables that will be improved from 1746 to 1757 thanks to observations of eclipses. At that time, each satellite had an empirical equation and Lalande noted in the ``Connaissance des Temps pour 1763" that ``the inclinations and the nodes of the orbits have variations which are not well known".

Then, these empirical tables were replaced by tables deduced from mathematical theories of the motions of the satellites. The first theories are due to Bailly, Lagrange (1766) and mostly to Laplace (1788) who built a complete theory of the motion of the Galilean satellites. Delambre (1791) built tables from Laplace's theory and from 6000 observations of eclipses. Damoiseau did the same and published his tables in 1836. Souillart improved Laplace's theory in 1880 and his work was used to build the tables published in the ``Connaissance des Temps". In 1891, other tables were published by Marth. At last, in 1910, Sampson published his tables founded on his new theory which will be published only in 1921. This theory was revitalized in 1977 by Lieske and fitted by Arlot in 1982 on 8856 photographic observations much more accurate than the old observations of eclipses. These last works are the basis of the ephemerides published in the ``Connaissance des Temps" until 2005. A new numerical integration including all the effects disturbing the motion of the Galilean satellites was built by Lainey in 2004 and fitted on observations made from 1891 to 2003. This integration is the basis of the ephemerides of IMCCE and is used in order to calculate phenomena by Jupiter as well as mutual phenomena.
Why such a large number of works and studies concerning the problem of the ephemerides of the Galilean satellites ? Since the first observations of the jovian system, the importance of the knowledge of the motion of the satellites appeared: the jovian system looked like a clock more perfect than the ones existing at that time and the eclipses were easy to observe. Lalande, in his ``Astronomy" (1792) wrote: ``they (the Galilean satellites) are continuously used by the astronomers for the determination of the differences in longitude between the different countries of the Earth (...); therefore it was important to have a sure theory of their motions". Cassini, in 1688, published a method to determine the geographic longitudes by the observation of the satellites of Jupiter. Thus, the publication of predictions of the eclipses was of the first importance.

Nowadays, the study of the motion of the Galilean satellites was made necessary by the need of accurate positions for the preparation of the missions of the space probes Pioneer, Voyager or Galileo to Jupiter and for the exploitation of the data that they provide us. But the nature of the jovian system (fast motions and numerous perturbating forces) makes it a particularly interesting field for the search of small gravitational or non-gravitational effects, not yet put into evidence, and for the study of the problems related to the resonances. The interest of the publication of positions and ephemerides of the Galilean satellites has been shown. It has to be noticed that the use of such tables of positions has always been difficult: in- terpolable ephemerides are not possible to make because of the rapidity of the motions. Therefore, tables of elements allowing the calculations of positions were published with a poor accuracy. Since 1980, tables of Chebychev coefficients were published in the ``Connaissance des Temps'': the accuracy of the calculated positions became near the one of the basic theory. Latter, a representation under the form of mixed functions depending directly on time was published: this has decreased the amount of data to be published representing one year of ephemerides. Now, coefficients are provided on CD Rom and the Connaissance des temps publishes positions near elongations in order to allow a test for the ephemerides. One must notice that diagrams showing the configurations of the satellites around Jupiter are also published. The accuracy is only 5 to 10 arcseconds which is sufficient for the identification of the satellites and the preparation of the observations. Most of the theories were fitted in the past on observations of eclipses. Unfortunately, these observations involve systematic errors, so, it is important to develop the different types of observations.

III - **THE DIFFERENT TYPES OF OBSERVATION OF THE GALILEAN SATELLITES**

The astrometric observation of a celestial body consists in the measurement, at a given time, of a physical quantity. Two types of observation are possible:
-- the regular observation which consists in the measurement of a physical quantity (for example an angular distance or a light flux, for a time choosen by the observer and referred to an absolute scale).
-- the observation of a phenomenon which consists in the determination of the time when a physical quantity has a remarkable value (mostly a maximum or a minimum for a variable quantity). These two types of observation need a clock for linkage to an absolute time-scale. However, the regular observation needs a sophisticated receptor in order to measure the absolute value of a physical quantity: for example angular distance calibrated on an absolute reference scale. The observation of a phenomenon needs to note only the time ``when something happens'' and to make a relative measure (some observations are a combination of these two types).

1. Observations of positions

a) visual observations
The interest of positional observation is to be able to observe anytime, not waiting for a phenomenon. The time of observation may be choosen, the number of observations is not limited and the observer may avoid bad meteorological conditions. As soon as it was permitted by the instrumentation, visual measures of distances and position angles between two satellites were made using micrometers. At Cape Observatory (South Africa) such very accurate measurements were made using an heliometer well adapted to such observations. At the beginning of the XXth century, photographic observations replaced them: they were precise too, and the plates could be kept after the observation was made.

b) photographic observations
The astronomical photography really began when the Henry brothers made a refractor named "equatorial photographique de la Carte du Ciel" the aperture of which is 33 cm and the focal length 3.43 m. The measurement of the plates (using a measuring machine named ``macromicrometer'') was more accurate than the observations made with micrometers. The reduction of the exposure used constants deduced from the positions of catalogued stars. The photographic observations of the Galilean satellites began near 1880-1890. Note that only short focus refractors were used at that time. During the years 1920- 1930, theoretical works concerning the Galilean satellites were interrupted as well as the observations. The ephemerides seemed to be very difficult to improve and astrophysical results were more appreciated by the astronomers. However, during the years 1960, studies on the dynamics of the Galilean satellites

started again because of the arise of the electronic calculators and be- cause of the preparation of the missions of the space probes toward Jupiter. Photographic observations were made again, but using long focus telescopes, because of the better photographic emulsions available.

c) CCD observations

The arrival of CCD receptors made useless the photographic plates thanks to the new facility, to the digitizing of the images and to the better sensitivity of the CCD compared to photographic emulsion. The problem came from the small size of the CCD receptors providing a too small field. This problem has been solved thanks to the new star catalogues very denses allowing the calibration of any field even small. Such a calibration allows to use any instrument, refractor or reflector, the stability of the field during the night being not necessary. Concerning the Galilean satellites, the only problem comes from their too bright magnitude making difficult the presence of the satellites and of reference stars simultaneously.

2. Observations of phenomena

a) Phenomena involving Jupiter

The Galilean satellites present phenomena because of the relative positions of the Sun, Jupiter and the Earth. These phenomena are: eclipses (when a satellite goes through the umbra of Jupiter), occultations (when a satellite is occulted by the disc of Jupiter), transits (when a satellite transits in front of the disc of Jupiter) and shadow transits (when the shadow of a satellite transits on the disc of Jupiter). The most observed phenomena are the eclipses because they are the most easy to observe: a satellite disappears and reappears from the shadow cone of Jupiter often far from the disc of the planet. The other phenomena need the observation of a satellite relatively close to Jupiter that decreases the signal/noise ratio.

All these phenomena have been observed during years and the eclipses have been the basis of most of the ephemerides. At the end of the XIXth century, the observation of the eclipses was improved: the first photometric lightcurves allowed to determinate more accurate observed times for the eclipses. More recently, photoelectric photometers appeared but were not very much used in spite of the quality of the data obtained: astronomers were no more interested in the dynamics of the Galilean satellites. When the interest for that reappeared, other technics of observation were more accurate. However, the reduction of the observations of eclipses may be improved and then their observations would be interesting.

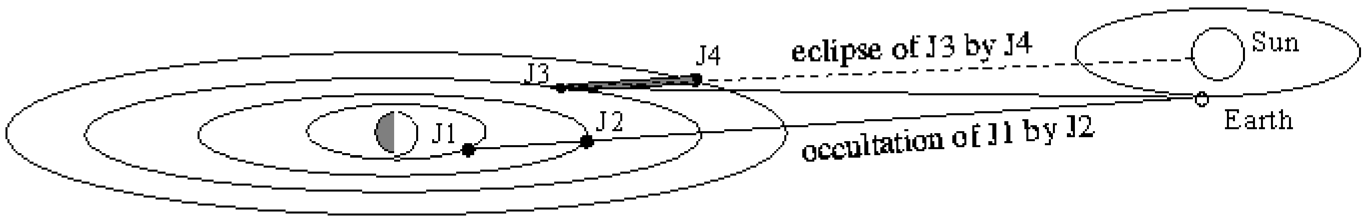

Fig. 1 – Definition of the mutual events.

b) Mutual phenomena

These phenomena are due to the relative positions between the Sun, the Earth and two satellites independently of Jupiter (see fig.1). Contrarily to the phenomena involving Jupiter which occur regularly each year (except for Callisto), the mutual events are possible only every six years. However, the absence of atmopshere on the Galilean satellites permits very accurate observations allowing the determination of the time, the duration and the amplitude of the observed phenomenon.

The next table shows the relative accuracy of the different types of observation: it is clear that the observation of mutual events allows to reach such accuracy that small undetected effects such as acceleration in the motion of the Galilean satellites may be searched.

ASTROMETRIC ACCURACY OF OBSERVATIONS OF THE GALILEAN SATELLITES

Observations	Type	Instrument		Individual error (") geocentric	km
Eclipses	visual		d<40cm	0,250	1000
Eclipses	visual photometry		d<40cm	0,200	800
Astrograph	photographic	f=3,4m	d<40cm	0,190	760
Eclipses	photoelectric photometry		d<60cm	0,150	600
Astrograph	photographic	f=5,2m	d<40cm	0,130	520
Héliometer	visual	f=2,5m	d<40cm	0,120	500
Astrograph	photographic	f=6m	d<40cm	0,100	400
Astrograph	photographic	f=10m	d<60cm	0,060	240
Astrograph	photographic digitized	f=10m	d<60cm	0,040	160
Mutual events	visual in mean quality site		d<40cm	0,055	220
Appulses	digitized images	f=20m	d=1m	0,030	120
Mutual events	images numériques en site urbain	f=20m	d=1m	0,015	60
Mutual events	photometry CCD in urban site		d=40cm	0,012	48
Mutual events	photometry CCD in mean quality site		d=80cm	0,010	40
Mutual events	photometry CCD in high quality site		d=1m	0,002	8

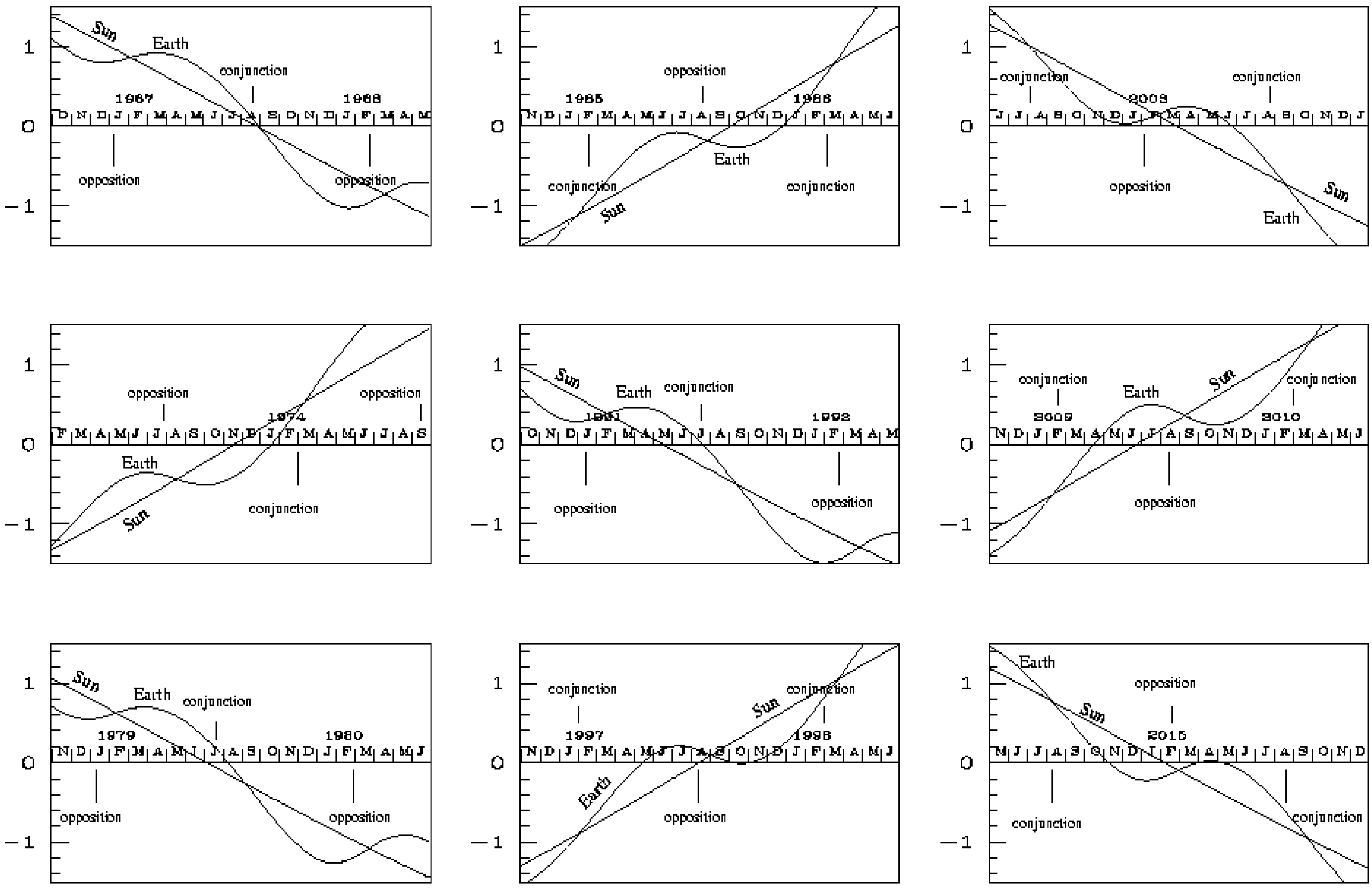

Fig. n°2: Jovicentric declinations of the Sun and the Earth (in degrees)

IV - **THE PREDICTION OF THE MUTUAL PHENOMENA**

Figure 1 shows how the mutual phenomena occur. When the Earth goes through the common orbital plane of the Galilean satellites (i.e. when the jovicentric declination of the Earth becomes zero) mutual occultations occur. Similarly, when the Sun goes through the common orbital plane of the Galilean satellites (i.e. when the jovicentric declination of the Sun becomes zero) mutual eclipses occur. Figure 2 gives the values of these jovicentric declinations for periods from 1967 to 2015. Mutual events are possible as long as these declinations stay near zero. At last, observations will be favorable depending on the geocentric declination of Jupiter: observations are easy in the northern hemisphere when the declination is positive or in the southern hemisphere when the declination is negative. The next table gives the values of these declinations for the different periods of mutual events.

Period	Declination of Jupiter
1967-1968	$+20^\circ$ to $+10^\circ$
1973-1974	-22° to -10°
1979-1980	$+12^\circ$ to $+8^\circ$
1985-1986	-22° to -14°
1990-1991	$+18^\circ$ to $+20^\circ$
1997-1998	-18° to -4°
2002-2003	$+23^\circ$ to $+18^\circ$
2009-2010	-20° to -10°
2014-2015	$+23^\circ$ to $+15^\circ$

A phenomenon occurs when the apparent distance between two satellites is smaller than the sum of the apparent radii (as seen from the Earth for the occultations and from the Sun for the eclipses (c). The phenomena may be partial, total or annular (as for the Moon). In the case of the eclipses, the eclipse may occur in the penumbra only, but this type of event may be more difficult to observe. If the motion of the satellites was circular and without perturbations, the calculations for the predictions would be sample: for each geocentric or heliocentric conjunction, a phenomenon would occur. It is not the case, and all the perturbating terms in the theory are to be taken into account. Thanks to electronic calculators, the calculations for the predictions may be completed without large errors. However, important differences may appear between predictions and observations: study of these differences may help for the improvement of the theory of the motions. Nothing will be developed in the present note, concerning the techniques of observation, the reduction of the data and the analysis of the observations which will be the subject of future Technical Notes.

(c) As a matter of fact, an eclipse is an occultation of the Sun by the eclipsing satellite, seen, from the eclipsed satellite. The velocity of light may be carefully taken into account for these predictions

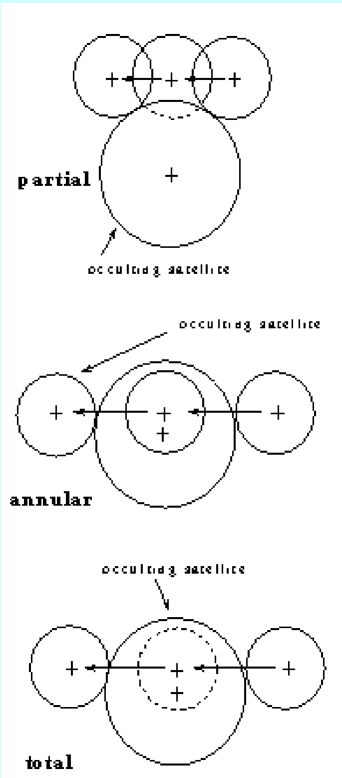

Fig. 3 – Occultations.

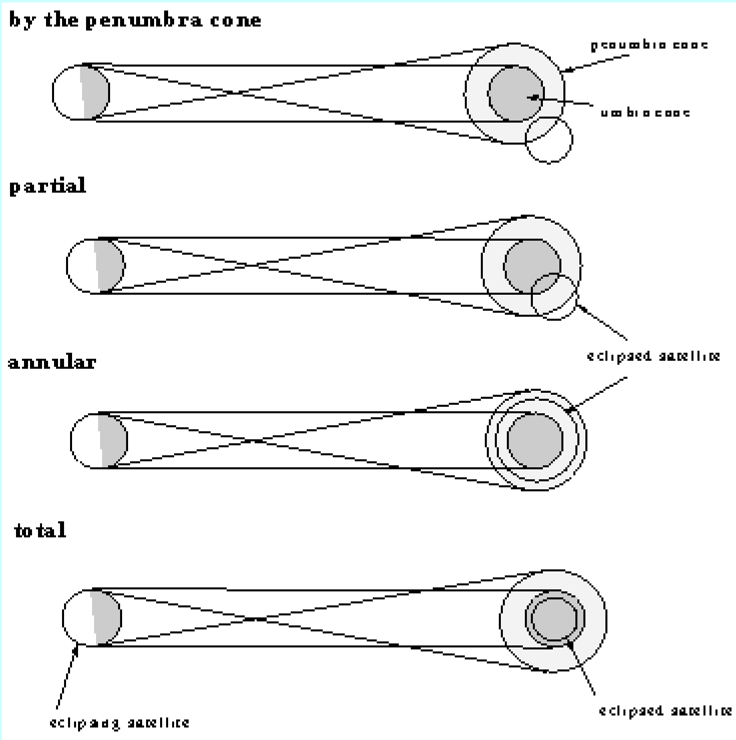

Fig. 4 – Eclipses.

VI - **THE CAMPAIGN OF OBSERVATIONS**

Such rare and accurate observations of events implied numerous efforts in order to make as many observations as possible during the short favorable periods. The visibility of a phenomenon depends on the location of the observers: therefore, an international cooperation is necessary between all the sites of observation in order to cover all the geographic longitudes. Before 1973, the predictions and the reduction of the data were difficult to make because of the absence of efficient electronic computers. Very few observations made before 1973 are available: some were made by the observers of eclipses by Jupiter. During the XIXth century, photoelectric receptors did not exist and only visual observations were made. Some occultations were only close approaches which looked like grazing occultations for the observers of that time.
In 1973, several sets of predictions were made and about 100 observations were performed since the period was very favorable.
In 1979, the period was not so favorable since events occurred mainly during the conjunction between Jupiter and the Sun. In order to avoid a lack of observation of such events, a particular effort was made and we gathered about 20 lightcurves.
In 1985, in spite of the negative declination of Jupiter, the period was very favorable. We coordinated a campaign gathering observers from France (Paris, Meudon, Grasse, Nice, Bordeaux, Pic-du-Midi, Observatoire de Haute- Provence), from Italy (Teramo, Catania), from Spain (Granada), from Switzerland (Jungfrau), from Brazil (Brasopolis) and from Chile (La Silla). Amateur astronomers from France, Belgium, Holland, Spain and Italy joined the campaign: the obtained data were often of high quality. About 160 lightcurves were made, covering the observation of 70 mutual phenomena.
In 1991, the period was less favorable but the declination of Jupiter was positive allowing observations by a large number of equipped sites. New sites in USA, India (Kavalur), Romania (Bucharest, Cluj-Napoca, Timisoara), Germany, Canada (Alberta), Japan, Yugoslavia, Bulgaria, Australia joined the campaign. 371 light curves were obtained covering 111 events from 56 sites. All these observations were made mainly with photoelectric photomultipliers but also using video cameras (SIT Vidicon), photodiode photometers or visually or photographically.
In 1997, the period was favorable because of the opposition of Jupiter occurring when the most events were observable. Unfortunately for the northern hemisphere, the declination of Jupiter was negative and the observations were easier from the southern hemisphere.
In 2003, everything was favorable: high declination of Jupiter and opposition at the best moment: 361 light curves of 116 events were recorded from 42 sites.

In 2009, the declination of Jupiter is not favorable to the northern hemisphere where most of the observers are but observations may be recorded even with Jupiter low above the horizon.

VII - **CONCLUSION**

These series of observations are interesting for the dynamical study of the jovian system but they gave us an experience allowing to improve our observational methods and techniques in order to increase the accuracy of the data. Observational techniques will be detailed in the next technical notes, but, some recommendations may be made:

-- the timing of each point of the lightcurve referred to a time-scale connected to UTC is absolutely necessary in order to be able to link all the observations made. Precautions must be taken in order to be sure of the time-scale used during the observation: verification of the time-scale before and after the observation with UTC. UTC is broadcasted by several networks and may be obtained by phone. The accuracy of the timing of each point of the lightcurve should be better than 0.5 second because of the relative velocity of the satellites which is around 10km/s;

-- the calibration in absolute magnitude is not absolutely necessary. The observation is done in relative photometry: the goal is to measure the relative magnitude drop of the signal before and during the event. Besides, absolute photometry is not always possible, especially in the case of a large absorption and of a small elevation above the horizon. However, a calibration made using solar-type stars is interesting. In the case of a variable transparency of the sky, a reference object (a star or another satellite) will permit the reduction of the observation: multi-channel photometers or two-dimensional receptors as CCD targets present a real interest: we will give details on these receptors in other technical notes. In any case, be sure of the linearity of the gain of the receptor used and avoid the saturation of the receptor at any time during the event.

In conclusion, don't miss these spectacular events, easy to observe, the observation of which allows to get very accurate data. The possible results of such observations and the international interest justify the efforts of coordinated campaigns of observations.