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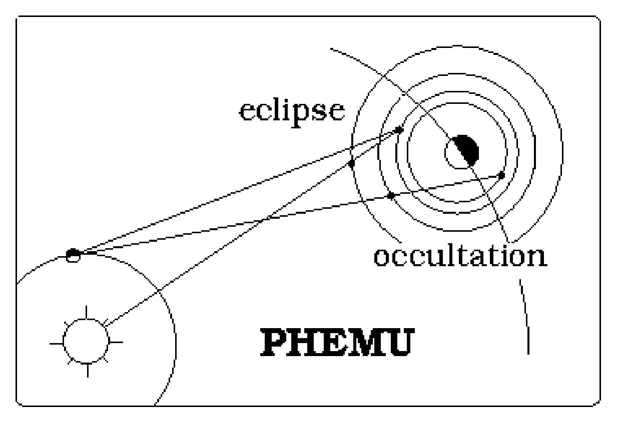

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BIBLIOGRAPHIC NOTE ABOUT MUTUAL PHENOMENA IN THE SATURN, URANUS AND PLUTO-CHARON SYSTEMS

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INTRODUCTION

This note collects scientific references of papers dealing with eclipse and occultation phenomena that are similar to the mutual events of Jupiter satellites from the point of view of the observing methods, data reduction, and final aims. Some of the common characteristics are the following ones: the events occur among bodies having similar dimensions; flux variations are generally rapid and each phenomenon can generally be observed in a single night; time sampling and synchronization are critical factors; reduction of lightcurves may lead to informations regarding position of the involved bodies in space and some physical properties such as their shape, albedo maps or surface scattering properties.

For these reasons we will consider here the mutual events between satellites of the Saturnian system, and also the events involving Pluto and Charon. Due to their similarity with these events and the rarity of their observations, eclipses of the Saturnian satellites by Saturn have also been considered here .
This note may be regarded as a complement to the PHEMU03 Technical Note n°2 which presents a rather complete list of works about the mutual events of the Galilean satellites.

1. Eclipses and mutual events of the Saturnian satellites

The first problem that had to be addressed about the phenomena in the Saturn system was the prediction of the events from reliable sets of orbital elements. In the past, Comrie (1934), for example, published an algorithm to compute the eclipses by Saturn. But mutual events of the Saturnian satellites were more difficult to accurately predict without the help of electronic computers. Only a few number of these observations was made (Aitken, 1909, Barnard, 1910, Innes, 1921, Comrie, 1921).

At our knowledge, the first modern attempt to get accurate predictions and organize their observations was made by Aksnes and Franklin (1978) for the satellites 1 (Mimas) through 7 (Hyperion). Nearly 300 mutual eclipses and occultations were predicted for a period going from October 1979 to August 1980, and eclipses of the satellites by the rings were also computed. To take into account the expected errors in the ephemerides, additional events were added, obtained with all satellite radii increased by 1000 km.

Previously, the Handbook of the British Astronomical Association regularly published the dates of the Saturnian phenomena by Saturn for each favorable period. Porter (1963) pointed out the occurrence of an occultation of Iapetus by Saturn and its ring. Peters (1975) gave his method to predict the phenomena involving natural satellites and their planets and publish a short list of such specific events by Saturn and the ring for the 1980 period.

First photometric lightcurves were obtained in 1980. Dourneau (1982) gives an account of the observation of two occultations, the first one of Dione by Tethys, and the second one of Tethys by Rhea, obtaining respectively one and three minutes of O-C, referred to the Aksnes and Franklin (1978) predictions. Since Tethys is involved in both the events, an error in its theory of motion is supposed. A counting photometer was used, while a photographic method complemented the observations. During this period several other authors published analysis of eclipses by the rings or by Saturn (Reitsema , 1978, Combes et al., 1980, Simth et al., 1981).

Soma and Nakamura (1982) observed five other mutual events from the Dodaira Station in Tokyo, detecting lightcurve asymetries, that they tentatively explain as the result of an inhomogeneus albedo.

Four observations of Saturnian mutual phenomena made in 1980 were then presented by Aksnes et al. (1984). The lightcurves were reduced using radii measurements by the Voyager probes. Strugnell and Taylor (1990) published a rather complete index of observations of the Saturnian satellites made during a time span of more than a century including these 1980 mutual events observations.

In 1993 Dourneau published a new theory of motion for the first eight satellites, using about one century of observations. By comparison to the 1980 mutual event observations he derived uncertainties in position of about 50-100 km for the involved satellites (III, IV and V).
Due to the high inclination of its orbit on the equatorial plane of Saturn, several eclipses of Iapetus occured in 1992 far from the period favorable to the other satellites. Soma (1992) gave these predictions.

In order to prepare the 1995-1996 opportunity several authors published their predictions of mutual events of the Saturnian satellites. Arlot and Thuillot (1993) gave predictions of mutual events and eclipses by Saturn with the aim of organizing an international observing campaign PHESAT95. Data referred to 182 mutual events and 163 eclipses by Saturn are presented. Some comparison are made with older observations. The accuracy expected from their observation is compared with the estimated errors of the available ephemerides. The first PHESAT95 workshop was organized in September 1994 in Bucharest, and the proceedings were published in Annales de Physique (Arlot and Stavinschi, 1996). Aksnes and Dourneau (1995) gave their own predictions of 198 events during the 1995-1996 opportunity.

These two set of predictions, as well as the different characteristics of the 1995 period, were presented at the Saturn Ring Plane Crossing workshop held at Tucson in 1994 (Nicholson, 1994). Emelyanov et al. (1994) gave their predictions of the mutual events. Emelyanov (1995) gave its method to predict the circumstances of some mutual events of the Saturnian satellites which could be difficult to interpret and to use for astrometric purpose.

Vienne and Duriez (1995) presented a new solution for the motion of the first seven satellites of Saturn. Their theory is derived by a semianalitical method and it is in good agreement with observations. A comparison is made with data published in Strugnell and Taylor (1990) and Aksnes et al. (1984).

Several authors published the observations made during the favorable period of observation of these phenomena of the Saturnian satellites: Consolmagno et al. (1996) and Hubbard et al. (1996) gave an account of the observation of an eclipse of Mimas by Titan. During the event the two shadows were observed to transit over the rings of Saturn. Photometry of the shadows provided informations on the

Titan's atmosphere. Emelyanov et al. (1997) gave their analysis of four mutual events observed in Crimea and Kazakhstan. The apparent relative positions were calculated with an accuracy up to 0.002". In March 1997, a workshop jointly organized by Bureau des longitudes and Catania observatory has been held in Catania, Sicilia, on the observation of mutual events and CCD astrometry. Several papers showed results obtained during the observations of the Saturnian phenomena in 1995 and 1996 (proceedings to be published). Preliminary results of the PHESAT95 campaign were published by Arlot et al. (1995), Arlot et al. (1996), Thuillot et al. (1996).

2. Mutual events of Pluto and Charon

The opportunity of observing Pluto-Charon mutual events occurs only once every 124 years. The sequence of events for the 1987 period was intensively followed thanks to an international campaign. Many astronomical observatories considered the photometry of these phenomena as a high-priority target since they can lead to orbital and physical parameters of this recently discovered satellite (see for example Binzel et al. 1988, 1991, Tedesco 1991, Tholen 1991).
First solutions of the orbit of the PlutoCharon system, soon indicated the possibility to observe mutual events, as discussed in Christy and Harrington (1980).
Mulholland and Binzel (1984) computed the predictions of the mutual events and modelized the expected lightcurves. They also showed that the events had not yet started till the beginning of 1983.

Binzel et al. (1985) published the first observed mutual eclipse, lasting a few hours. The importance of the observations of Pluto-Charon events for the determination of several physical parameters is stressed. Indications regarding diameters, surface albedo distribution on one hemisphere of the planet, the orbit of the satellite, mass and densities of the two bodies, are expected.

A table of predictions for 1986 is published by Tholen (1985). The list gives data for 81 mutual events, and the maximum predicted light drop during the considered period is about 0.15. Dunbar and Tedesco (1986) discussed numerical and analytical models of the lightcurves due to mutual events, taking into account the effects of shadowing. Lightcurves of the Pluto-Charon events seem to agree well with the model within the estimated measurement errors, and the event series are predicted to end in 1990. The second part of this work has been published by Buratti et al. (1995).

Reinsch and Pakull (1987) presented photometric observations of the Pluto-Charon system made in the period 1982-1986 including observations of mutual eclipses in april 1986. A determination of the radii gives the values of 580 km and 110 km fot Pluto and Charon respectively, both smaller than spekle interferometric measurements. Mean density and geometric albedo are similar to those published for Triton and the icy satellites of Jupiter and Saturn.
Later, Aumann and Walker (1987) combined IRAS observations, visual flux and mutual-events constraints to evaluate the thermal model of Pluto and Charon. This model are consistent with eclipse observations of Dunbar and Tedesco (1986) but not with Reinsch and Pakull (1987).

The main result is the compatibility of Pluto and Charon with the standard asteroid model typical for the icy Galilean and Saturnian satellites.
Mulholland and Gustafson (1987) discussed the role of the diffraction effects, suggesting that the observations of the Pluto-Charon mutual events could show a dependence on both wavelenght and telescope aperture.

Tholen et al. (1987) tabulated in two papers the predictions of 89 Pluto-Charon events in 1988. Photometric measurements of a comparison star used during 1987 are given, and standard stars for the photometric calibrations of other stars are suggested. Other predictions are published by the same team in Tholen et al. (1989).

During two events of 1987 Sawyer et al. (1987) obtained time-resolved spectra of the PlutoCharon system. The spectrum of Charon was featureless, but that of Pluto allowed to identify the presence of methan absorption bands.

Tholen and Hubbard (1988) showed that the diffraction effects predicted by Mulholland and Gustafson (1987) are absent in the observations.
The parameters of the system allow the use of simple geometrical optics to study the events. In Binzel (1988) a general description of the importance of the Pluto-Charon events is given. An observing program in this sense is proposed for the McDonald Observatory. The same project is discussed in Binzel (1991).

In a following paper, Binzel (1989) described the process of data reduction leading to the determination of physical and geometrical parameters of the Pluto-Charon system. The possibility of inferring the surface albedo distribution is also discussed.

Blanco et al. (1989) in the first one among three papers showed the results of Pluto-Charon events observations made at the Catania Astrophysical Observatory (Serra La Nave observing station) and at the ESO Observatory (La Silla, Chile). At the first site a 91-cm reflector was used, equipped with a photon counting system and B, V filters. At the second site the 61-cm Bochum telescope was used with a similar photometer and U, B, V filters. This first paper deals with the events observed between March and July 1988. No significant deviation of the observed contact times from the predicted ones is detected. A difference in the slope of the light loss between superior and inferior events in B and V is detected.

In Blanco et al. (1991) this fact is explained in terms of the spectrophotometric data for Pluto and Charon (Pluto is redder due to the lack of methan frost). Blanco et al. (1994) presented the results of the observations of the last events, observed between May and June 1989 at Serra La Nave. A disagreement with the predicted times of the lightcurve deepest point for two events is pointed out.

Marcialis (1990) presented the results obtained from spectrophotometric observations of the events in visible and near-infrared light. Difference in surface composition between Pluto and Charon were detected. Pluto appear dominated by a methan deposit, while Charon by water ice. Albedo variations on Pluto's surface are correlated with compositional ones, since dark regions appear to be redder and depleted in methan relative to bright regions. Accurate radii were computed, and an albedo model tested. From new internal models, the role of viscous relaxation for Pluto was assessed and consequences over the extension of the topographic features derived.

Tedesco (1991) reviewed the methods used for comparing HST observations of the Pluto-Charon system with the observed lightcurves. The aim of this study was the determination of models of the system and the mass-ratio of the bodies.

The results are also rewieved by Stern (1992), who points out the relevant consequences over the theories for the Pluto-Charon formation and the critical points still to be solved.

Buie et al. (1992) discussed the application of a maximum entropy image reconstruction for the inversion of the observed lightcurves, deducing a surface albedo map on a grid 59 x 29 for Pluto and Charon. The results are compatible with those obtained by Buie and Tholen (1989) with a spot model. Charon appears darker with a single-scattering albedo as low as 0.03, while Pluto seems to own a bright south polar cap. Another map of the surface albedo of Pluto is described by Young and Binzel (1993). It is derived using three different models, used to describe the brightness of Pluto's sub-Charon hemisphere. The whole procedure is validated with comparison to maps derived from synthetic data. The presence of a bright south polar cap is confirmed.

Reinsch et al. (1994) presented the results derived from 18 satellite transits and 15 eclipses and occultations of Charon, together with ordinary photometric observations. All data were obtained between 1982 and 1990. Refined orbital parameters and a geometric albedo map of Pluto's subCharon hemisphere are derived. General features of the previous maps (bright polar regions, highly contrasted variations) are confirmed.

Young and Binzel (1994) discussed an important discrepancy (around 4 %) on the Pluto's radius measurement as derived from a 1988 stellar occultation with that obtained from the mutual phemonena. A possible explanation is given by means of a contribution coming from a possible limb darkening of the disk of the two bodies involved. This was neglected in the mutual events modelling, leading to radii underestimation.

Albrecht et al. (1994) compare the albedo maps derived from the observations of mutual phenomena to high quality images obtained by the Faint Object Camera of the Hubble Space Telescope after the installation of corrective optics. Raw images were already diffraction-limited, nevertheless attempts to improve the resolution by image restoration were made. A qualitative comparison shows that the two independent results are in good agreement.

Drish et al. (1995) used Pluto light curves to generate surface albedo maps. They presented a new light curve inversion that can incorporate the case of mutual phenomena. The paper briefly discusses the different relevance of mutual phenomena and rotational variations over the determination of albedo maps. Mutual phenomena could give useful informations on the Charon-facing hemisphere of Pluto.

In the period spanning from 1980 to 1994, Grundy and Fink (1996) obtained spectrophotometric observations of the Pluto and Charon system, looking for variations in Pluto's methane absorptions and continuum slope due to daily or secular evolution. The mutual events observations made during that period were also taken into account for a comparison.

Tholen and Buie (1997) used Hubble Space Telescope images taken by the Wide Field and Planetary Camera to improve the orbit of Charon and found a high orbital eccentricity. The orbit semi-major axis is in good agreement with the older determinations used to compute Pluto and Charon radii by mutual occultation events.

The same Hubble Space Telescope images allowed to extract individual lightcurves and B-V colour indexes. By combining the measurements with mutual events observations Buie et al. (1997) found that the colour of Charon should be globally uniform and confirmed a reddish B-V colour for Pluto around 123 and 289 degrees of planetocentric longitude.

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