PLANETARY OCCULTATIONS OF BRIGHT STARS

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All occultations by planets of stars brighter than 3·52 magnitude have been calculated for AD 1900–2100. For the first magnitude stars, this period is extended to AD 1000–3000. The circumstances of such occultations are discussed; the mean frequency of planetary occultations of first magnitude stars is compared with the probability for mutual planetary occultations.

Introduction

Occultations of bright stars by planets, though relatively rare phenomena, have been observed on several occasions. Perhaps the most famous cases were the Venus–Regulus event in 1959[1], the occultation of β Sco by Jupiter and its satellite Io in 1972[2] and the Mars–ϵ Gem occultation in 1976[3]. Such occultations are of astrophysical interest, since information can be obtained about the structure of planetary atmospheres, although in several cases more reliable data are at present obtained by spacecraft. Furthermore, the large-scale optical properties of the atmosphere can be studied during these events, while planetary occultations may provide also an accurate value of the planetary diameter and of the planet's position. But the most interesting application is probably the exploration of the direct environment of planets, as came out in 1977 when the rings of Uranus were discovered during an occultation with a faint star. In 1981 there will be an occultation of a second-magnitude star by Venus, visible in Europe. As far as we know, however, no complete list exists of the past and future planetary occultations of bright stars; at present the situation is such that these phenomena are announced quite shortly before they take place. Therefore we traced all planetary occultations of stars brighter than magnitude 3·52 for the period AD 1900–2100.

Obviously, occultations of the first-magnitude stars are the best events; for these stars the list has been extended from AD 1000 to 3000. From this long time interval one gets a fair impression of the mean probability for such an event.

General considerations

The extreme latitudes which may be reached by a planet are +8°·6 and −8°·6; these values are possible for Venus. Therefore, a star lying closer to the ecliptic may be a candidate for a planetary occultation. However, these extreme latitudes can only be reached for certain longitudes of Venus: *for any other longitude Venus remains always closer to the ecliptic.* Actually, for each planet there exists a band near the ecliptic in which the planet always is situated. For the inner planets the entire ecliptic is in this band, and the ecliptic may be crossed at any longitude by such a planet. This means also that if a star is close enough to the ecliptic, an occultation by an inner planet is geometrically possible. For stars farther away from the ecliptic, this possibility depends on its longitude. On the other hand, for the outer planets there exist parts of the ecliptic which can never be reached. The possibility for occultation always depends on the exact position of the star in this case.

Table I

List of all Stars Brighter than Magnitude 3·5 for which Occultations with one of the Bright Planets are Possible

A possibility is indicated by +. *Mercury–ϵ Gem cases were only possible* before 1980 (see text).

Star	*Magnitude*	*Mercury*	*Venus*	*Mars*	*Jupiter*	*Saturn*	
η Tau	3·0	−	+	−	−	−	
ζ Tau	3·0	+	+	−	−	−	
η Gem	3·2–4·0	+	+	−	−	+	
μ Gem	3·2	+	+	−	−	+	
ϵ Gem	3·2	(+)	+	+	−	−	
δ Gem	3·5	+	+	−	−	+	
α Leo	1·3	+	+	−	−	−	(Regulus)
γ Vir	2·9	−	−	+	−	−	
α Vir	1·2	+	+	−	−	−	(Spica)
α Lib	2·9	+	+	+	−	−	
π Sco	3·0	−	+	−	−	−	
δ Sco	2·5	+	+	+	−	−	
β Sco	2·9	+	+	+	+	−	
σ Sco	3·1	−	+	−	−	−	
α Sco	1·2	−	+	−	−	−	(Antares)
θ Oph	3·4	+	+	+	−	−	
λ Sgr	2·9	+	+	+	−	−	
ϕ Sgr	3·3	−	−	+	−	−	
σ Sgr	2·1	−	+	+	−	−	
τ Sgr	3·4	−	−	+	−	−	
π Sgr	3·0	+	+	−	−	−	
β Cap	3·2	−	+	−	−	−	
δ Cap	3·0	−	−	+	−	−	

In Table I a list is given of all stars brighter than magnitude 3·52 for which planetary occultations are geometrically possible. From the list it can be seen a first-magnitude star may only be occulted by Mercury or Venus. Table I reflects the situation at the present time. Because of the secular variations of the orbital elements of the planets, the band in which a planet is always situated is slowly changing its form and its position between the stars. This effect, combined with the proper motions of the stars requires continuous revision of Table I in the course of the centuries: some of the present combinations will become impossible, while new ones should be added to the list. For instance, Mercury–ϵ Gem occultations become geometrically impossible from the year 1980, and will not return to the list for 20 000 years. On the other hand, around 2500, Venus–ϕ Sgr occultations will become possible. This combination has been absent from Table I for many tens of thousands of years.

For any star to be occulted by a given planet there exist only two lines passing through the star and crossing the orbits of the occultating planet and the Earth. In this paper we will call these lines the *nodes* for occultations. Since there are only two such nodes for any planet–star combination, there are only two specific configurations of a planet and the Earth with respect to the Sun where an occultation with a given star can actually take place. Therefore, there are also only two dates in a year on which a conjunction between the star and the planet may lead to an occultation. For Venus–Regulus, for instance, these dates are at present around July 7 and September 30; they are slowly changing due to the precession of the Earth. For an occultation at a given node the circumstances are completely fixed and will be the same for the next one at this node. So the occultations take place at a fixed elongation from the Sun, while the apparent diameter, phase and parallax of the planet will be the same. Also, the direction of the motion of the planet between the stars will be the same. At the other node these circumstances are also fixed, but are, in general, completely different from the first node. These circumstances are only affected by the secular changes of the planetary orbits and the proper motion of the stars, and therefore only very slowly changing in time. In general, for one of the nodes the movement of the planet has a northern component with respect to the ecliptic and for the other one a southern component. We will call the first one the *ascending* node, and the second one the *descending* node.

Circumstances for occultations

An occultation of a star may occur while the planet is in direct or in retrograde motion. Which of these two possibilities occurs depends on the planet–star combination: for Venus–Regulus occultations the motion is direct for both nodes, while for Venus–Antares the motion is different for the nodes. If the motion is direct, the movement of the planet with respect to the star is fast and the apparent planetary diameter small, so that an occultation will have a short duration. If the planet is in retrograde motion, its apparent diameter can be much larger and its speed is considerably lower, so that an occultation will take much more time. An extreme case is an occultation which takes place if the planet is stationary in both longitude and latitude during occultation. In that case the duration can

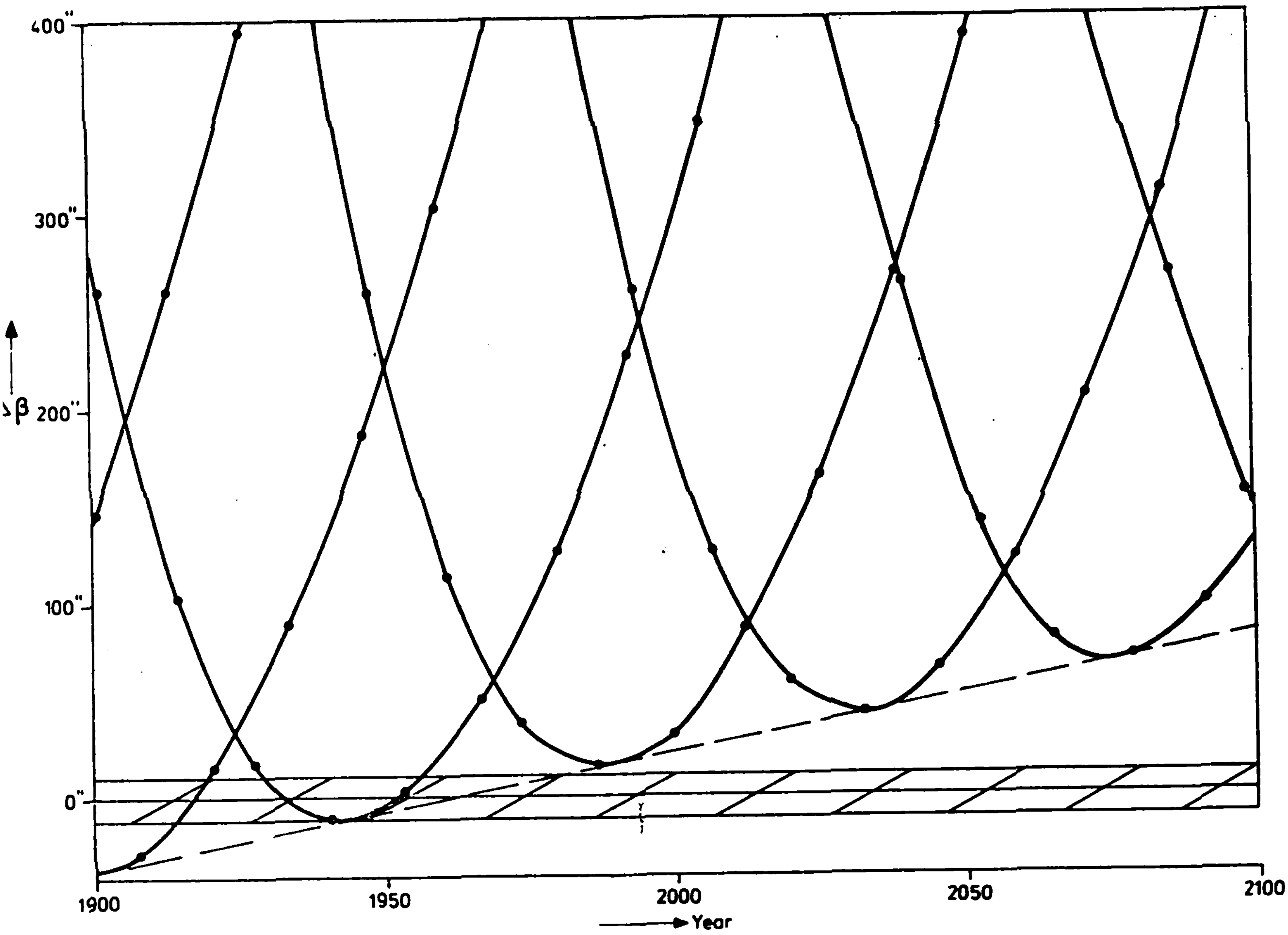

FIGURE 1. Plot of all close (less than 400″) Mercury–ϵ Gem conjunctions. $\Delta\beta$ is the latitude of the star minus the latitude of the planet. The solid lines connect conjunctions with 13 years' interval; the dashed line touching these parabolas represents the most northern position of the planet which can be reached. The band around $\Delta\beta = 0$ indicates the area where occultations take place, as for instance in 1940 and 1953. Due to the secular changes in the planetary orbit and the proper motion of the star, from 1980 no occultation is possible, as can be seen from the figure. The plot is for the period 1900 to 2000.

be very large indeed. Now it appears that the probability of a given star being occulted by a given planet (for instance, expressed in minutes of occultation per century) is almost the same for both nodes*. This implies that for a node where the duration of a central occultation is short, more occultations can be expected as in the reversed case. In fact, if the apparent planetary diameter is large and its speed low, much of its 'occultation probability' is consumed at each occultation and consequently only few such occultations may be expected. Apparently, the number of occultations at the node is proportional to the velocity of the planet with respect to the star, expressed in the number of its own apparent diameter per time interval. Therefore, especially for the inner planets, occultations in retrograde motion will be much rarer than the ones in direct motion. It may be interesting to note that for mutual planetary occultations a similar

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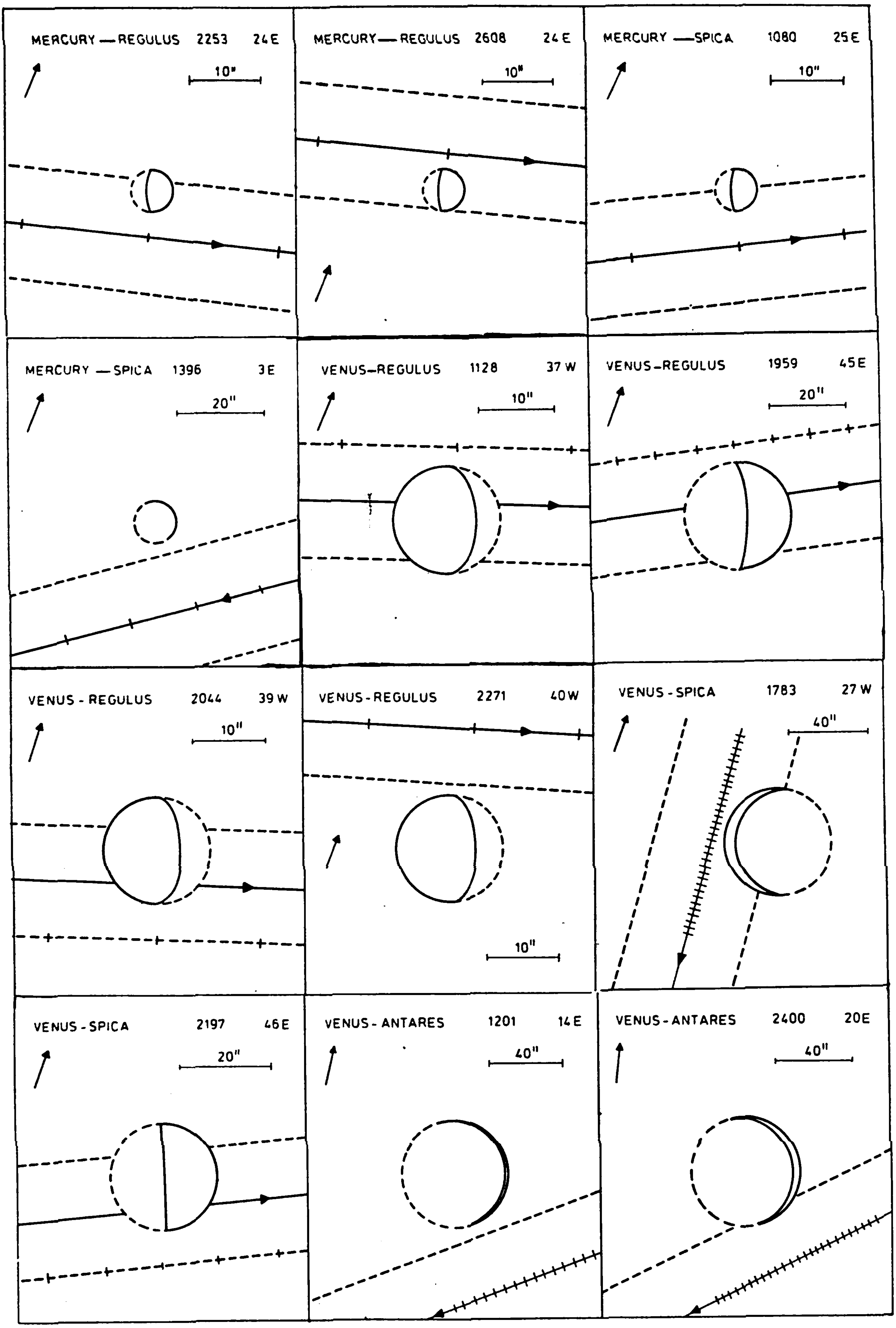
*This statement holds exactly for circular planetary orbits and a star with latitude zero, but is also a good approximation in the general case.


MERCURY — REGULUS 2253 24E
10"
MERCURY — REGULUS 2608 24E
10"
MERCURY — SPICA 1080 25E
10"
MERCURY — SPICA 1396 3E
20"
VENUS–REGULUS 1128 37W
10"
VENUS–REGULUS 1959 45E
20"
VENUS - REGULUS 2044 39W
10"
VENUS - REGULUS 2271 40W
10"
VENUS - SPICA 1783 27W
40"
VENUS - SPICA 2197 46E
20"
VENUS - ANTARES 1201 14E
40"
VENUS - ANTARES 2400 20E
40"

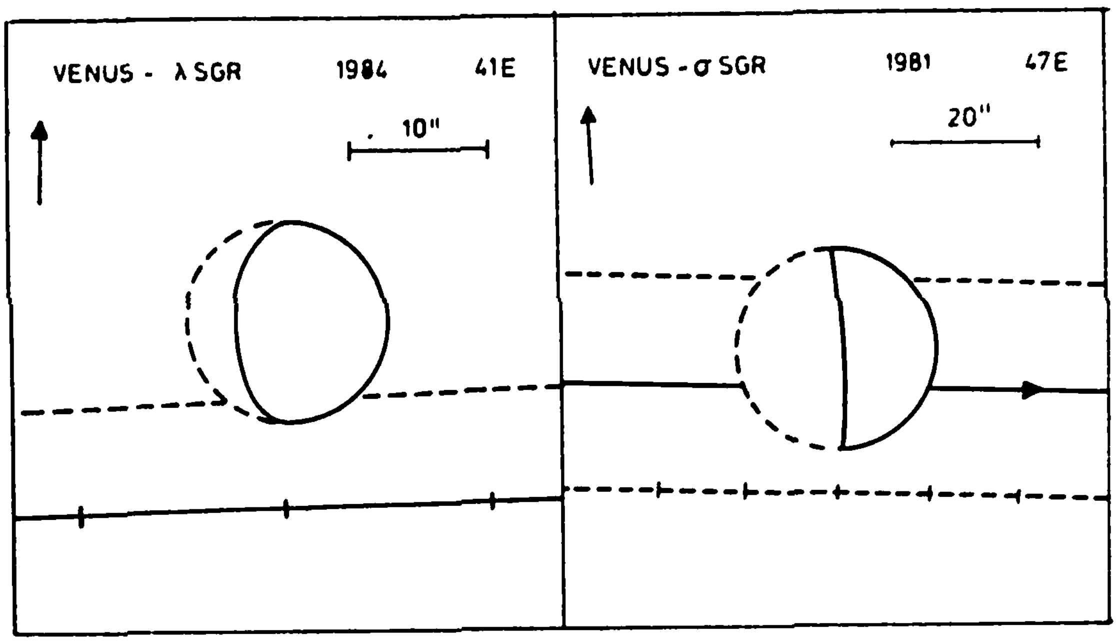


FIGURE 2. (*On opposite page and above.*) Relative path of the first-magnitude star with respect to a planet during an occultation or a very close approach for AD 1000–3000. The two remaining occultations for fainter stars for the twentieth century are also added to the figure. Ecliptic north is up; the celestial north is indicated by an arrow. The solid lines represent the path for a geocentric observer; the dashed lines the maximum displacement due to the parallax. Time intervals of five minutes have been indicated on either the solid or a dashed line.

rule can be formulated. This explains why only so few of these occur near opposition of inferior conjunction[4]. The same holds for close planetary conjunctions[5].

The probability of a star being occulted depends only on its position. It appears that this probability rises sharply if a star is situated at a position which can just be reached by the planet. So, at the end of an era in which a star can be occulted by a certain planet, the probability for occultations rises sharply within a few years, and drops then to zero as the occultation becomes geometrically impossible. For the Mercury–ϵ Gem combination this has been the case recently. To illustrate the effect, in figure 1 close approaches of Mercury to the star are plotted. The solid lines connect conjunctions with 13 years' interval (a periodicity also known from transits[6]); they have a parabolic shape. The dashed line touching these parabolas represents the extreme possible latitude of the planet at the longitude of the star. From the figure it can be seen that from 1961 no geocentric conjunction is possible where the centre of the planet is north of the star; from 1980 occultations become impossible as seen from any place on Earth. Moreover, the 'density' of close conjunctions (and thus the probability for occultation) is at its highest when the dashed line crosses the region where occultations occur, thus as the occultations reach the point they become geometrically impossible. Such behaviour is a well-known phenomenon in physics; it is, for instance, also responsible for rainbow formation[7]. Indeed, the rainbow represents a borderline of an area on the sky which is illuminated by a specific combination of reflection and refraction in a raindrop. At this border the intensity of light (= the probability of finding a photon) reaches a maximum in the same way as the probability for an occultation does before it becomes geometrically impossible.

For the actual calculations of the occultations we proceeded as follows. Close approaches of the planets to stars have been calculated taking the well-known planetary formula of Newcomb/Ross and Galliot using a computer method. If the geocentric least distance between the centre of the planet and the star is less than the sum of the semidiameter and the parallax of the planet, an occultation occurs somewhere on Earth. Results of these calculations are discussed in the following paragraphs.

Occultations of bright stars

Figure 2 represents the relative path of the first-magnitude stars with respect to the occulting planet from AD 1000 to 3000. Very close approaches are also included, since within the uncertainty of the formulae an occultation cannot be excluded in these cases either. Time intervals of 5 minutes in the relative positions are also indicated in the figure. From this it is clear that the duration of a central occultation may vary greatly. Two occultations of fainter stars are also included in the figure; these are the only remaining events for the rest of our century and will be discussed in the next paragraph. We will now briefly discuss the occultations of the first-magnitude stars. All close conjunctions (<3′) for the near future (1980–2010) will also be mentioned in the text.

Mercury–Regulus. There are two occultations, both in the future. They take place in 2253 August 1 and 2608 August 6; both near the ascending node. The other node should produce occultations around September 11, at 18°W of the Sun. Close conjunctions in the near future will take place in 1990 July 29 (2′) and AD 2004 September 10 (3′).

Mercury–Spica. Two cases occur, one for each node. The one in AD 1396 September 27 is dubious; it took place very close to the Sun: the other one was in 1080 September 9. In the near future Mercury will never come closer than 3′ to Spica; the shortest approach will be in 2007 September 22 (5′) near the ascending node.

Venus–Regulus. There are four cases between 1000 and 3000. The 2271 case is a dubious one. These four occultations have been discussed by Meeus[8]. The 1959 July 7 occultation was widely observed in Europe. The shortest approach in the near future will be in 2004 October 3 (9′).

Venus–Spica. There are two cases, one for each node. On 1783 November 10 an occultation took place while Venus was almost stationary in longitude. As far as we know this occultation was not observed, although it was visible on the east coast of America. Note the difference in duration of a central occultation between the 1783 case ($1\frac{1}{2}$ hours) and the one at 2197 September 2 (12 minutes). For the near future, Venus remains always far from this star.

Venus–Antares. There will be one case and one near miss, both at the same node. At this node, Venus is in retrograde motion. Note the difference between the path of 1201 October 30 and 2400 November 17 as the result of the secular changes of the orbital elements of Venus. In this case (retrograde motion and Venus near the Earth) the circumstances of the occultations are quite sensitive for such changes. As for the 1201 case, an occultation remains possible within the uncertainty of the planetary formulae used. At the other node (around October 16) Venus is in direct motion, at 44°E from the Sun. Although, statistically speaking, occultations at this node are much more likely, no case is found between AD 1000 and 3000. For the near future, Venus remains far from Antares.

Other stars

Table II presents all occultations of the remaining stars brighter than magnitude 3·52 for 1900–2100. Some remarks follow:

Venus–β Sco, 1906. Attempts to observe the phenomenon from New Zealand were frustrated by clouds[9].

Mercury–ϵ Gem, 1953. Observed in daylight from South Africa. This is the only occultation by Mercury observed so far[10]. From 1980, Mercury–ϵ Gem occultations are geometrically impossible (see figures 1 and 2).

Jupiter–β Sco, 1971. Observed widely. Also, Io occulted β_2 Sco[2]. Occultations of fainter stars by Jupiter have been discussed by Meeus[11]. Occultations of β Sco by Jupiter are relatively frequent: between 1000 and 3000 there are five cases, in 1200, 1876, 1971, 2561 and 2908.

Mars–ϵ Gem, 1976. Observed widely in North America. For this planet, the 'central flash' occurring at the middle of a central occultation was discovered[3].

Venus–σ Sgr, 1981. Visible in Europe near sunset[12]. In eastern Europe the Sun will already be below the horizon during the event. The path of Venus with respect to this second-magnitude star is given in figure 2.

Venus–λ Sgr, 1984. This last occultation of the twentieth century will be visible in a small part of northern America.

In the twenty-first century there remain only four occultations, while there is a pause of 50 years between the 1984 case and the next one. From Table II it is clear that no occultation by Saturn is visible between 1900 and 2000. As for the planets Uranus and Neptune, only the former may occult a star brighter than magnitude 3·5. This concerns α Lib, but the star is not occulted in this period. Even when one extends the search down

TABLE II

LIST OF ALL OCCULTATIONS WITH STARS BRIGHTER THAN MAGNITUDE 3·5 VISIBLE BETWEEN 1900 AND 2100

The least distance between the star and the centre of the planet (expressed in arc seconds) for a geocentric observer is indicated by d; $\pi+s$ means the sum of the planetary semi-diameter and the parallax, also expressed in arc seconds. ET = ephemeris time, and *elong.* = elongation.

	Date	ET	*elong.*	*d*	$\pi+s$
Venus –β Sco	1906 Dec. 9	18^{h}	15W	18·9	61·8
Venus –η Gem	1910 July 27	3^{h}	31W	0·9	12·6
Mercury–ε Gem	1940 June 10	2^{h}	20E	10·3	11·2
Venus –α Lib	1947 Oct. 25	2^{h}	14E	4·2	10·4
Mercury–ε Gem	1953 June 11	11^{h}	19E	3·4	10·9
Venus –α Leo	1959 July 7	14^{h}	45E	3·8	12·6
Jupiter –β Sco	1971 May 13	19^{h}	170W	16·6	23·1
Mars –ε Gem	1976 Apr. 8	1^{h}	81E	2·4	9·1
Venus –σ Sgr	1981 Nov. 17	16^{h}	47E	5·0	27·9
Venus –λ Sgr	1984 Nov. 19	2^{h}	39E	13·7	15·1
Venus –π Sgr	2035 Feb. 17	15^{h}	42W	14·8	16·8
Venus –α Leo	2044 Oct. 1	22^{h}	39W	4·7	15·3
Mercury–α Lib	2052 Nov. 10	7^{h}	3W	11·6	17·8
Mars –θ Oph	2078 Oct. 3	22^{h}	71E	2·9	10·0

to sixth-magnitude stars, no case for Uranus nor for Neptune is found[13].

Additionally to Table II, we found for 1980–2010 only five approaches of a planet to a bright star with a minimum separation less than 3′, at an elongation of more than 30° from the Sun. These are Venus–σ Sgr (1989), Venus–λ Sgr (1992), Mars–θ Oph (1999), Venus–θ Oph (2000 and 2008).

Finally, we give a short note on *mutual planetary occultations*. Here, there are 11 possible combinations between the planets Mercury to Saturn, compared with five possibilities for an occultation of a first-magnitude star by a planet. Although mutual planetary occultations are reputed to be of an extreme rarity[14], it turns out that they are five times more frequent than the occultations of first-magnitude stars. Counting the number of close conjunctions (separation less than 600″) and taking into account the mean value of the semidiameter and parallax of the planet, we calculated the mean frequency of occultations with bright stars to be one in 190 years. For a mutual occultation, we find in the same way one per 40 years. Probably, the 'gap' between 1818 and 2065[4,5] in mutual planetary occultations is responsible for the suggestion of their extreme rarity.

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