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Association of Corotating Magnetic Sector Structure with Jupiter's Decameter-Wave Radio Emission

C. H. Barrow

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Goddard Space Flight Center
Greenbelt, Maryland 20771

ASSOCIATION OF COROTATING MAGNETIC SECTOR STRUCTURE WITH JUPITER'S DECAMETER-WAVE RADIO EMISSION

C. H. Barrow*

Planetary Magnetospheres Branch

Laboratory for Extraterrestrial Physics

NASA/Goddard Space Flight Center

Greenbelt, Maryland 20771

* On sabbatical leave from the Department of Physics, University of the West Indies, Kingston, Jamacia, W.I.

ABSTRACT

Chree (superposed epoch) analyses of Jupiter's decameter-wave radio emission taken from the new Thieman (1979) catalog show highly significant correlation with solar activity indicated by the geomagnetic Ap index. The correlation effects can be explained in terms of corotating interplanetary magnetic sector features. At times when the solar wind velocity is relatively low, about 300 to 350 km/s, a sector boundary can encounter the Earth and Jupiter almost simultaneously during the period immediately before opposition. After opposition this will not normally occur as the solar wind velocities necessary are too low. The correlation effects are much enhanced for the three apparitions of 1962-1964 during which a relatively stable and long-lived sector pattern was present. Chree analyses for this period indicate periodicities, approximately equal to half the solar rotation period, in the Jupiter data.

I. INTRODUCTION

In a recent paper (Barrow, 1978; subsequently referred to as Paper I) the general principle has been investigated that the decameter-wave radio emission from Jupiter is somehow associated with solar activity and the solar wind. This was demonstrated for the fourteen apparitions between 1960-1975 by Chree (superposed epoch) analyses in which Jupiter events, taken from the University of Colorado Radio Astronomy Observatory (UCRAO) Catalog (Warwick et al., 1975), represent epochs for a table of geomagnetic Ap index values. The confusing effects of changing Earth-Sun-Jupiter geometry and varying solar wind velocity were taken into account. Artificial periodicities in the Jupiter data, due to Io revolution and to Jovian and Earth rotation, were identified and, in some caes, removed.

Although highly significant correlation appeared from these studies it was clear that not all of the Jupiter data were correlated with the Ap index. Correlation was much enhanced by selection of Non-Io events for the epochs but considerable fluctuation and discrepancy remained which varied somewhat from year-to-year. This raises the possibility that the correlation indicated is not direct but the resultant of effects involving Jupiter's radiation, the Ap index and some other variable or variables. It has been suggested, for example, from studies limited to relatively short periods of time, that solar shock waves may be responsible for the Non-Io emission (Dryer et al., 1975; Terasawa et al., 1978) or that the Jupiter radiation may be indirectly associated with Forbush decreases (Kovalenko, 1971). It must be remembered, however, that in general Jupiter events occur considerably more often than do either solar shocks or Forbush decreases.

In the present paper, evidence is presented to associate some of the Non-Io radio emission with interplanetary magnetic sector structure.

II. CHREE ANALYSIS

A comprehensive catalog of Jupiter activity has recently been compiled by Thieman (1979) at the Goddard Space Flight Center (GSFC). This catalog combines most of the fixed frequency events that have been observed by almost every group in the world since the apparition of 1957. Included are the observations at 16.7 and 22.2 MHz compiled at GSFC by Alexander et al. (1977). These data have been taken from a round-the-world network of observing stations and are thus largely free of the effects of terrestrial rotation.

The calculations described in Paper I have recently been repeated, using the new Thieman catalog, with a consequent improvement in statistics, and for 16 MHz, almost complete elimination of periodicities associated with both Earth rotation and Io revolution. More events are available for analysis at 18 and 22 MHz but these frequencies also contain many single observatory listings which tend to introduce periodic effects due to Earth rotation. While the overall conclusions are essentially the same for all three frequencies they are most unambiguously demonstrated at 16 MHz. Following the procedure described in Paper I, the data have been separated into two parts: two month periods before opposition and two month periods after opposition. The delay peaks in each case should, therefore, be differently positioned due to corotational effects between the Earth and the Sun (Paper I) and this affords an additional test for correlation.

Chree analyses for 16 MHz events, catalogued between 1960 and 1977, are shown in Figure 1. In both cases peaks appear, above the 99% confidence levels, which are considerably better defined than those presented in Paper I. There is no indication of spurious periodicity other than, perhaps, solar rotation in the extreme left of the before opposition case. The positions of the correlation peaks are indications of the mean solar wind velocities that are implied by the analyses. Provided that these correspond to reasonable values (indicated, approximately, by horizontal bars in Figure 1) the exact positions of these peaks are not critical as far as possible correlation is concerned.

The most striking feature of Figure 1 is that in the before opposition case it is again the secondary peak of Paper I, close to epoch, that predominates over the direct case. In terms of the simple model taken as a starting point for Paper I, this corresponds to the situation in which a stream of solar particles is directed first towards Jupiter and then, after almost a whole solar rotation, towards the Earth. A first encounter of the stream with the Earth is apparently missing, unless this is represented by the peak on the extreme left. This latter peak implies a solar wind speed of about 275 km/s which is inordinately low, although it might be explained by the small deceleration of about 30 km/s which, according to Smith and Wolfe (1978), appears to take place in the solar wind between 1 and 5 AU. Similar peaks do not appear in the 18 and 22 MHz Chree tables, however. There is no obvious explanation of this effect in terms of the particle model and we now seek an explanation in terms of some other quantity which might reasonably be expected to relate to both Jupiter's radio emission and to the Ap index.

III. INTERPRETATION

In paper I it was noted that periodicities of approximately half the solar rotation period* were present in some of the Chree tables. According to Ward (1960), the Ap index may sometimes contain periodicities given, in descending order of probability, by 27/N where N = 1,2,3,4,5,6. Ward found that N = 2 may often be present, N = 3,4 may sometimes be present and N = 5,6 only occasionally present over some finite number of solar rotations. Nowadays these sub-periodicities can be associated with rotating interplanetary magnetic sectors (Wilcox and Ness, 1965). The sector boundaries between regions of opposite polarity extend spirally into space and, in a stationary frame of reference, the sector structure rotates with the Sun and may sometimes persist for a number of solar rotations. It is now well known (Smith and Wolfe, 1978) that the interplanetary sector structure extends to the orbit of Jupiter and beyond; many of the associated corotating interaction regions (CIRs) that form between the slow and the fast solar wind are formed beyond the orbit of the Earth. Over 90% of these CIRs are accompanied by forward shocks when the solar wind reaches 5 AU.

The forms of pairs of Archimedean spirals 180° apart are compared for typical solar wind velocities in Figure 2. These highly idealized pictures might represent streamlines of stationary flows in a corotating system, opposite polarity boundaries in a pattern of two equal sectors, similar polarity boundaries in a pattern of four equal sectors, or any other property of the interplanetary medium that might be associated with spiral structure. It can be seen that the mean distances of the Earth and of Jupiter are such that, close to opposition for low solar wind velocities of the order of

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* Note that the solar rotation period seen from Jupiter is approximately 25.4 days and not 27.3 days, as seen from the Earth.

300 km/s, one end of the same spiral will encounter Jupiter almost at the same time that the other end encounters the Earth. For higher solar wind velocities of about 550 to 600 km/s, one spiral will encounter Jupiter almost at the same time that the opposite spiral encounters the Earth. At opposition, these coincidences will occur for velocities of approximately 290 and 575 km/s, respectively. In principle, therefore, if the Jupiter decametric emission were to be associated somehow with any feature that exhibited spiral structure, a Chree analysis would indicate a correlation peak only slightly displaced from epoch, if the geometrical configuration of the Earth-Sun-Jupiter system and the prevailing solar wind velocities were appropriate and if the structure were to be sufficiently stable and well-defined. It is suggested that the before opposition peak in Figure 1, and also similar effects in Paper I, may be explained by this principle which will now be examined more specifically.

Consider the 300 km/s spirals shown in Figure 2(a). Coincidence of a spiral encounter with the Earth and with Jupiter will occur at opposition if the spiral is defined by a solar wind velocity of about 290 km/s. Within the 60 day period immediately before each opposition the Earth-Sun-Jupiter angle will vary between 60° and zero. During this period, coincidences can occur from spirals defined by solar wind velocities ranging from just below 300 km/s up to almost 350 km/s. This is shown schematically in Figure 3. For slightly higher solar wind velocities, negative delays (Jupiter active before the spiral encounters the Earth) may be seen, typically about -3 to -7 days for 400 km/s. The range of values arises from corotational effects, as discussed in Paper I.

For single spiral coincidence to take place after opposition the solar wind velocity would have to be below 290 km/s and this seldom occurs. For higher solar wind velocities, after opposition, the spiral must rotate about the Sun before it can encounter Jupiter after first having encountered the Earth. In this situation a range of delays will be observed, depending upon the prevailing solar wind velocity and corotation within the 60 day period after opposition used for the Chree analyses. Typically, for 400 km/s these would be about 14 to 18 days.

IV. DISCUSSION

According to Hundhausen (1972) and to Svalgaard and Wilcox (1978), the solar wind speed is usually rather low, down to about 300 km/s, at any sector boundary, while higher speeds, up to about 750 km/s, tend to follow the boundary. This is confirmed independently by the work of Kennedy et al. (1974) in a study of solar wind effects upon the Non-Io Jupiter radiation; they find that, for the period October, 1967 to May, 1968, the date of sector passage at the Earth occurred at a local minimum of solar wind speed followed by a local maximum some four or five days later. Sector boundaries are now regarded as being due to a warped current sheet that separates positive and negative magnetic fields in interplanetary space. According to Wolfe and Smith (1978), the current sheet crossings in the outer solar system have a tendency to occur within reaction regions. It is not yet known if these crossings coincide with the interface at 5 AU, although at 1 AU it has been found that sector boundaries often occur at or near the peak density preceeding an interface. Thus the Chree diagrams in Figure 1 may be regarded as indicators of correlation between Jupiter's Non-Io emission and geomagnetic activity, interplanetary magnetic field structure, or CIRs. The corresponding delays may differ by a day or two, of course.

The positions of the Chree peaks in both the before and the after opposition sections of Figure 1 seem to be consistent with the foregoing and suggest the possibility of correlation via some recurrent low solar wind speed spiral structured process.

It is emphasized that, whatever the process of correlation, it must depend upon some recurrent feature of the low speed solar wind. If this were not the case, a solar wind feature that lasted up to only four days (the maximum time for a radial stream to be directed first at the Earth and then at Jupiter during the 60-day period before opposition) should be sufficient to produce a correlated effect with a Chree diagram delay of about 24 to 29 days for a solar wind speed of 300 km/s. This might then be expected to be the dominant effect with a peak close to epoch less well defined, if shown at all. In fact, the opposite seems to occur in most of the Chree analyses studied and, for this reason, an interpretation based upon spiral structure is preferred. Radial flow and spiral structure are interdependent, however, and any possible dependency on the one will have an interpretation in terms of the other, even if one interpretation may be more plausible than the other.

The solar rotation period is sometimes apparent in the Chree analyses although often it appears as half rotation periods, the case N = 2 in Ward's (1960) study. This is particularly conspicuous for the three apparitions 1962-1964, shown in Figure 4; a period during which the magnetic sector structure was well-defined and relatively stable. Data from the UCRAO catalog (Warwick et al., 1975) have been used for this figure as the Thieman (1979) catalog does not contain a complete listing for this period at 16 MHz. Significant periodicities, approximating to half the solar rotation period, are apparent in both sections of the figure.

Ness and Wilcox (1967) have examined the period 1962-1964, during which a 27-day recurrence period was observed in the sector pattern near the Earth. In Figure 5, taken from their paper, the sector pattern has been overlaid on the daily magnetic character index C9. To this have been added the two-month periods, adjacent to each Jupiter opposition, for the 1962, 1963 and 1964 apparitions. From Mariner-2 observations in 1962 through IMP-1 observations in 1963 an IMP-2 observations in 1964, the sector patterns are essentially vertical when plotted on the 27-day Bartels diagram. According to Coleman et al. (1966), the four-sector pattern observed by IMP-1 during the second half of 1963 apparently developed from the two-sector pattern observed previously by Mariner-2. Periodicities of some 12 to 15 days can be seen corresponding to the leading and trailing edges of similar polarity sectors. These are comparable with the periodicities indicated in Figure 4.

An alternative, less likely, possibility is that opposite sector boundaries in a pair might encounter the Earth and Jupiter at the same time. This is indicated schematically in Figure 6 for idealized pairs of symmetrical spirals. It can be seen that rather higher solar wind velocities are necessary for this to occur, greater than 575 km/s in the before opposition configurations and about 430 to 575 km/s in the after opposition configuration, assuming the pairs of spirals to be perfectly symmetrical, which is unlikely and not essential for a coincidence to take place. Generally, the Chree analyses conducted in this paper as well as those in Paper I do not indicate after opposition effects in which the correlation peak is close to epoch. It is for this reason that we are lead to the conclusion that the <u>single</u> sector boundary, defined by a <u>low</u> solar wind speed, is the activating agency rather than higher velocity solar wind features. It is worth noting, however that for 1974, the after opposition events recorded by the GSFC network at 16.7 MHz show very pronounced peaks corresponding to delays of 14 days before epoch and 12 days <u>after</u> epoch. These are, of course, separated by approximately one solar rotation period and it is possible that each may indicate coincident opposite sector encounters. Certainly the solar wind speed tended to be exceptionally high at times during this period (King, 1977). The correlation peaks can also be explained, however, by single spiral coincidence where the spiral is defined by a solar wind velocity of about 450 km/s. This seems to be a more plausible explanation and is verified to some extent by the minimum values preceding solar wind speed enhancements given by King (1977).

Some caution is necessary in the use of the Chree method when the range of days before and after epoch is comparable with the overall period of time considered. End effects arise, comparable to those in a lagged cross correlation, and these end effects are not eliminated even if the actual number of epochs considered is quite large. A general indication can, no doubt, be obtained but, rigourously, the significance of any conclusions drawn under these circumstances is questionable. There is also a practical limitation on the number of days before and after epoch that may be considered for any length period as the confidence level criteria may be reduced unrealistically if this number is too large.

V. SUMMARY AND CONCLUSIONS

Chree analyses of Non-Io Jupiter events taken from the new Thieman (1979) catalog show highly significant correlation between Jupiter's decametric radio emission and the geomagnetic Ap index, during the period 1960-1977. This correlation appears to be largely free of periodicities due to both Earth rotation and Io revolution for the 16 MHz data. The correlation is much enhanced for the three apparitions of 1962-1964 during which a well-defined relatively stable sector pattern persisted. Periodicities, approximating to one half the solar rotation period, are apparent in the analyses for this period. This tends to suggest an interpretation in terms of magnetic sector structure although other explanations are possible. The correlation may represent the delay between a geomagnetic enhancement following the encounter of a sector boundary and associated conditions at the Earth and the encounter of the same sector boundary at Jupiter. This would be consistent with a suggestion by Oya and Moriaka (1977) who, from auto- and cross-correlation studies of Jupiter's radiation and the geomagnetic Kp index for the apparitions of 1974 and 1975, propose sector boundary encounter with the Jovian magnetosphere as a possible means of enhancement of the main (A) source emission. If the sector boundary encounter is defined by low solar wind speeds, the encounters at the Earth and at Jupiter can take place almost simultaneously during the 60-day period immediately before opposition. This is unlikely to occur after opposition because of the very low solar wind speeds that would be necessary.

While some of the preceeding discussion is in terms of spiral structure and magnetic sector structure, other interpretations cannot be excluded. Any property that showed spiral features and related to the Ap index would correlate to some extent with the Jupiter emission. It is for this reason that "an association" of magnetic sector structure with the Non-Io radiation is referred to rather than a correlation. At the present time, however, the magnetic sector interpretation seems to be rather more plausible than other possibilities, because of the 1962-1964 results.

Terasawa et al. (1978) have suggested that solar shocks may be associated with the Non-Io Jupiter emission. This is consistent with the present work as (Smith and Wolfe, 1978) most CIRs are accompanied by forward shocks by the time that the solar wind reaches the orbit of Jupiter. If the density increase and associated dynamic pressure increase, that often accompanies a sector boundary at 1 AU, continues this association out to 5 AU (Section IV), it is possible that these may provide the physical stimulus to create conditions appropriate for the enhancement of Non-Io decametric emission. Kovalenko's (1971) result is also consistent as, according to Smith and Wolfe (1978), there appears to be some correspondence between CIRs and decreases in cosmic ray intensity.

Hopefully, the forthcoming Voyager encounters will provide data for testing these ideas further. Kaiser and Alexander (1977) have shown that, at certain times, the terrestrial kilometric radiation is well correlated with the auroral AE index. The AE index also correlates with the product VB_z, both of which terms influence geomagnetic activity through the interplanetary electric field $\vec{E} = -\vec{V} \times \vec{B}$ (Burlaga and Lepping, 1977). It will be interesting to compare in situ measurements of these quantities with the Jovian decameter and hectometer emission.

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FIGURE CAPTIONS

Figure 1. Chree analyses of Jupiter events against the geomagnetic index Ap for 16 MHz data between 1960 and 1977. The broken lines indicate 99% confidence levels.

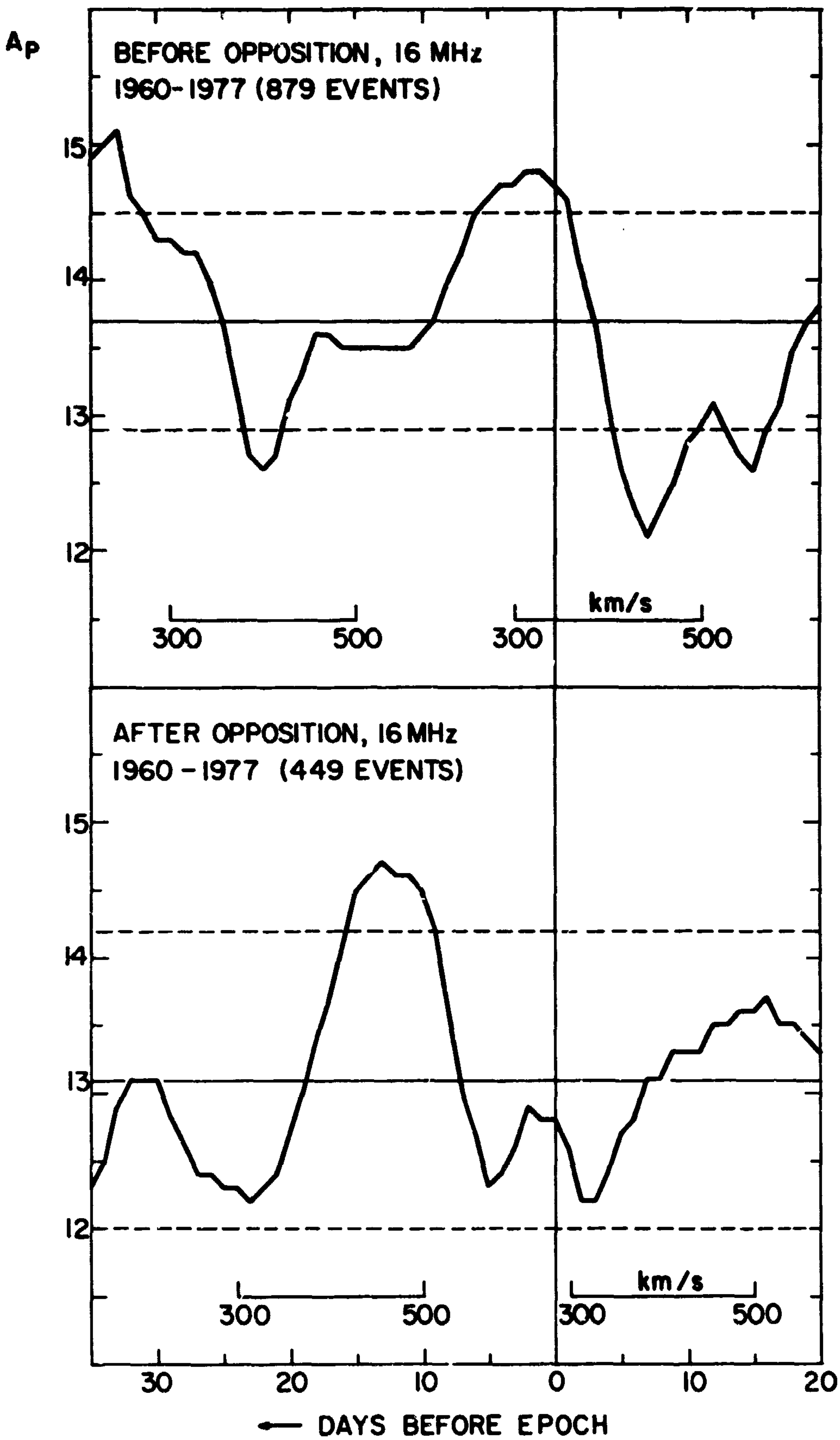
Figure 2. Idealized Archimedean spirals for typical solar wind velocities. The numbers on the Jupiter orbits represent the number of days that must elapse before the corresponding spiral end will encounter Jupiter.

Figure 3. Idealized low solar wind velocity spirals that could produce coincidences or negative delays during the 60-day period immediately before opposition.

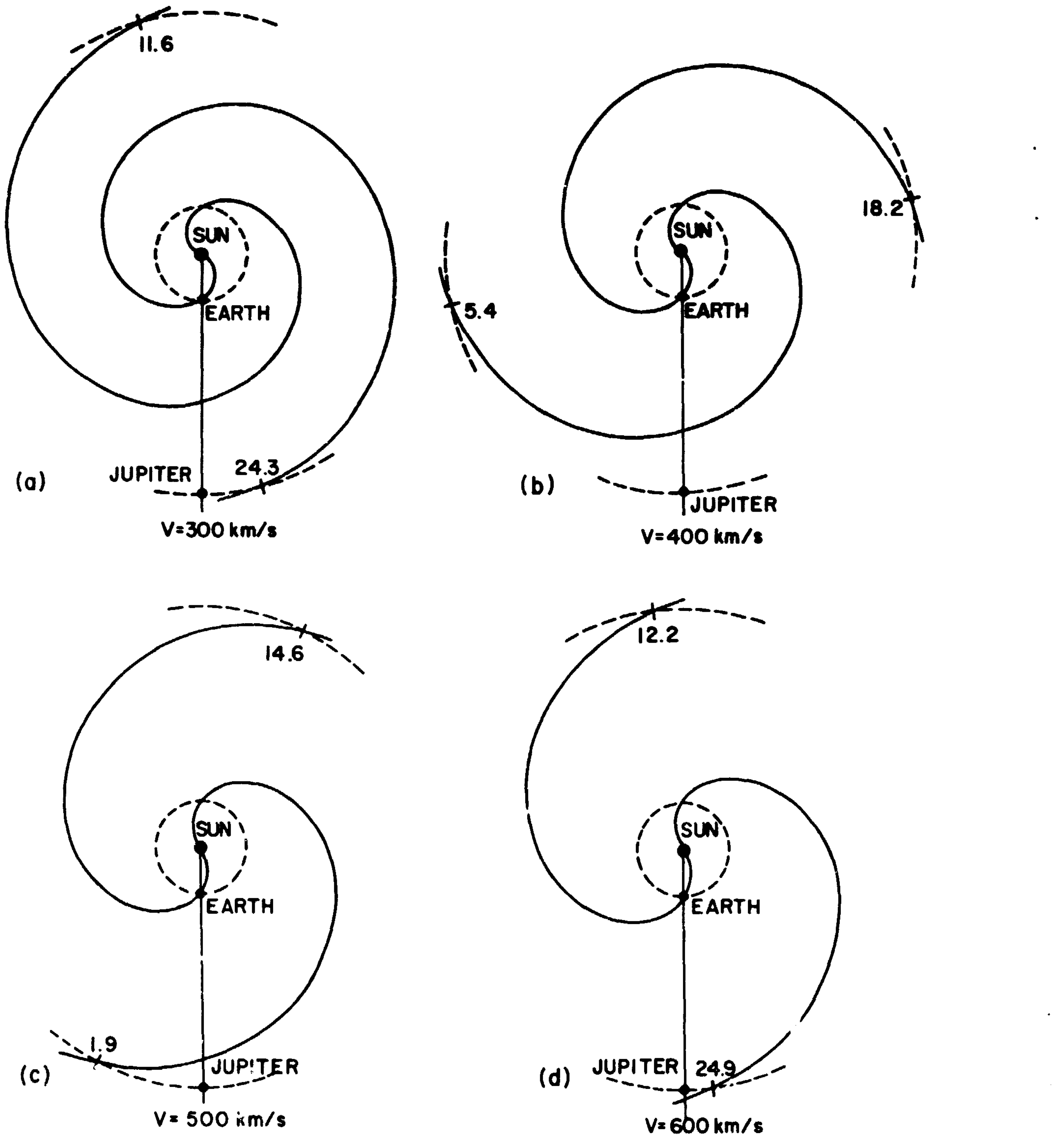
Figure 4. Chree analyses of Jupiter events against the geomagnetic index Ap for swept-frequency data between 1962 and 1964. The broken lines indicate 99% confidence levels. Significant periodicities approximating to half the solar rotation period are apparent in both the before and the after opposition analyses.

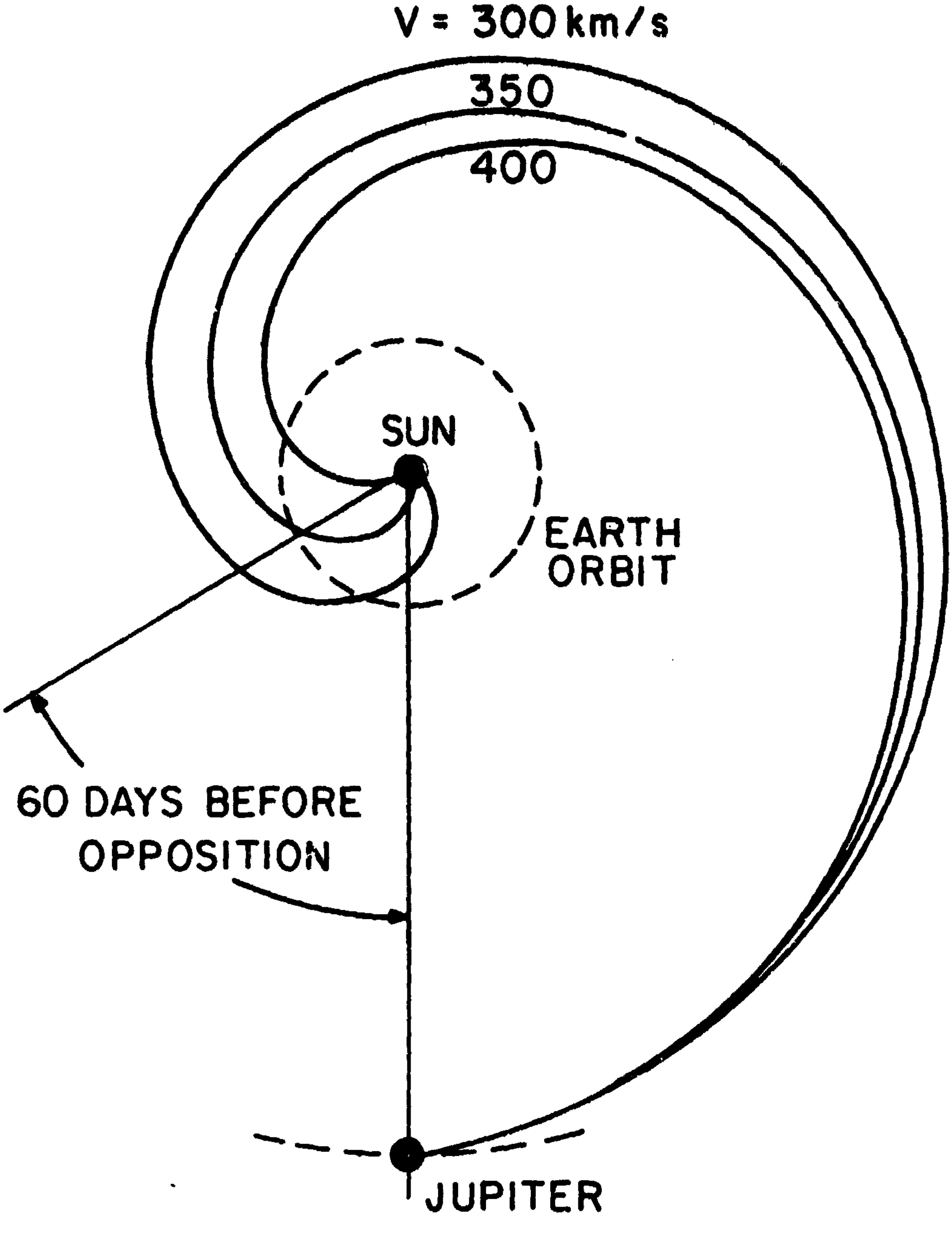
Figure 5. Sector structure of the interplanetary magnetic field overlaid on the daily magnetic character index C9 from Ness and Wilcox (1967). The two-month periods adjacent to three oppositions of Jupiter have been added and are indicated as J1, J2, and J3 for 1962, 1963 and 1964, respectively.

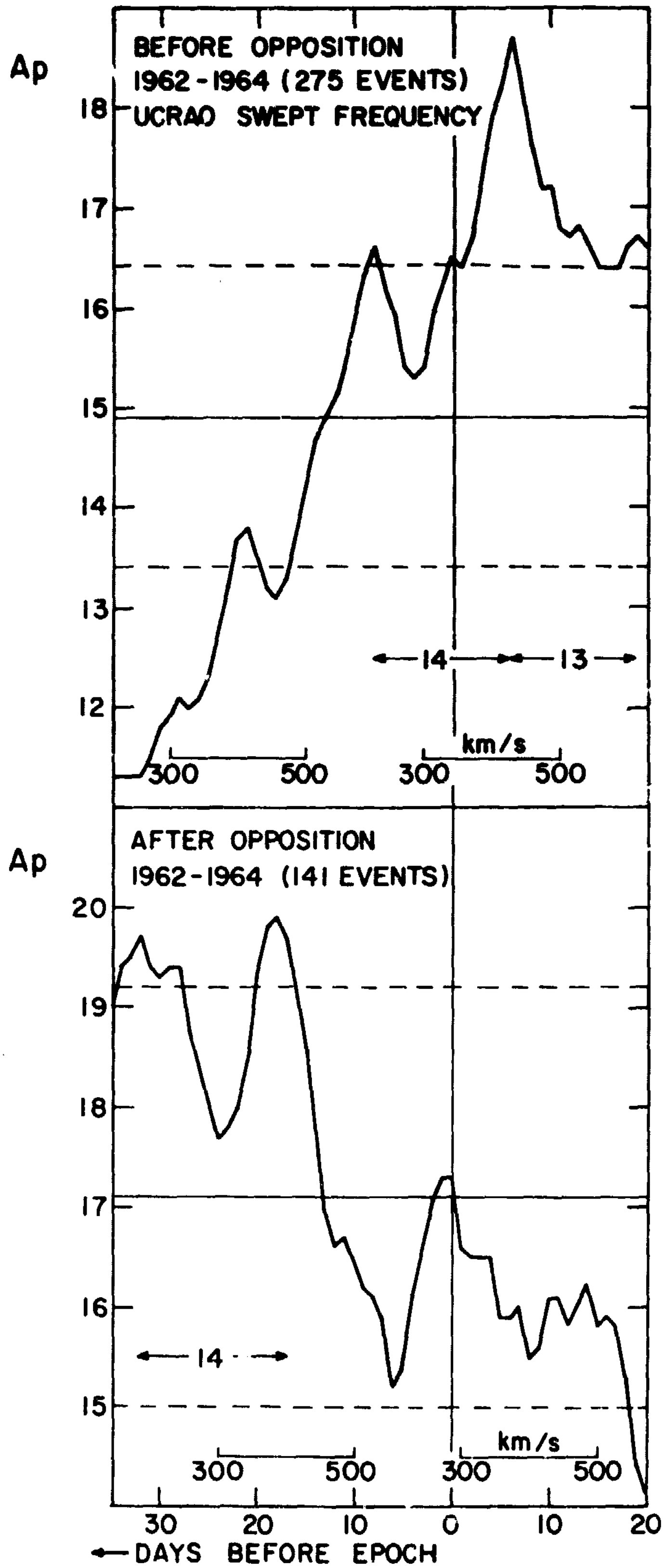
Figure 6. Idealized pairs of symmetrical spirals 180° apart that might encounter the Earth and Jupiter at the same time.



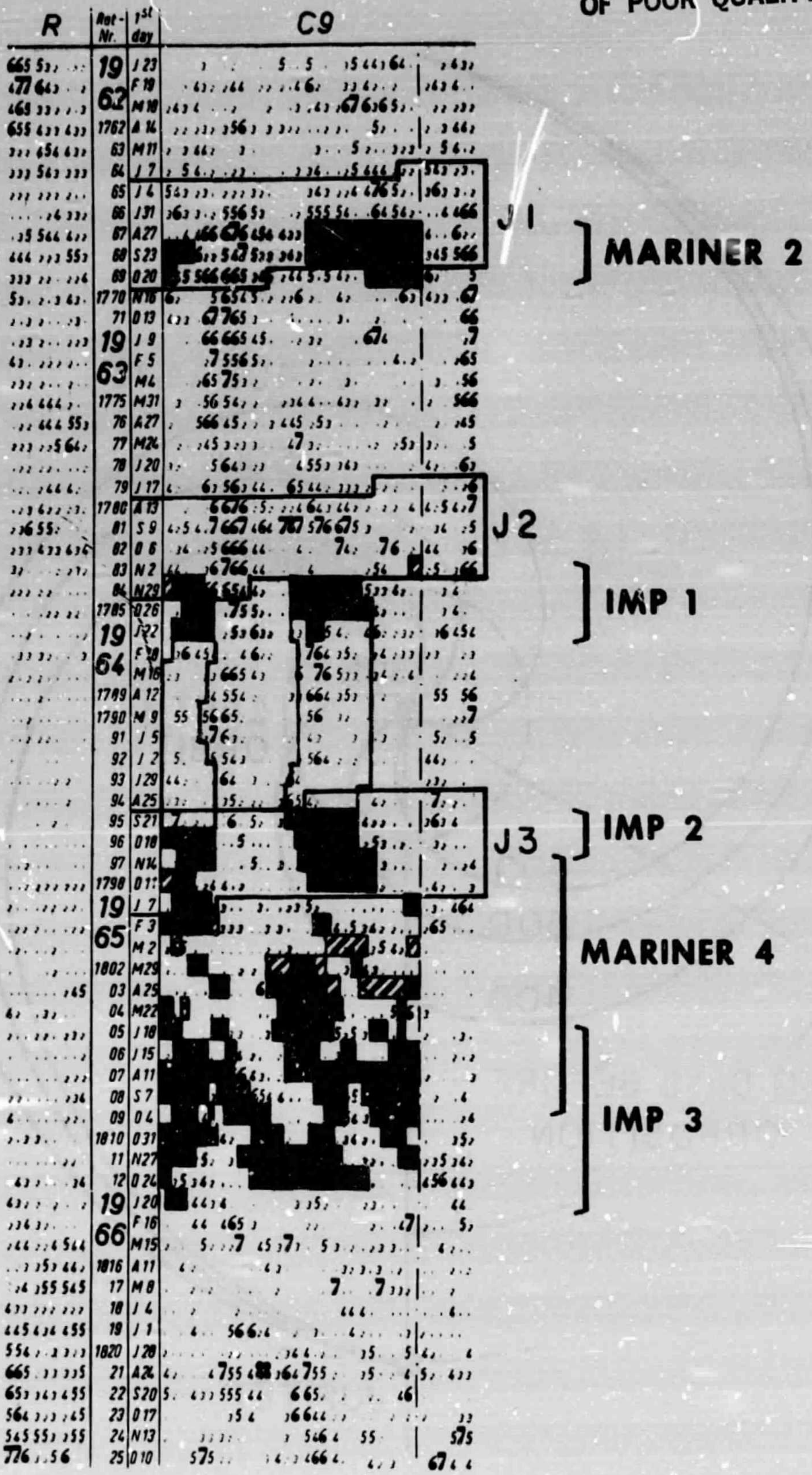
AP
BEFORE OPPOSITION, 16 MHz
1960-1977 (879 EVENTS)
15
14
13
12
300
500
km/s
300
500
AFTER OPPOSITION, 16 MHz
1960 - 1977 (449 EVENTS)
15
14
13
12
300
500
km/s
300
500
30
20
10
0
10
20
← DAYS BEFORE EPOCH

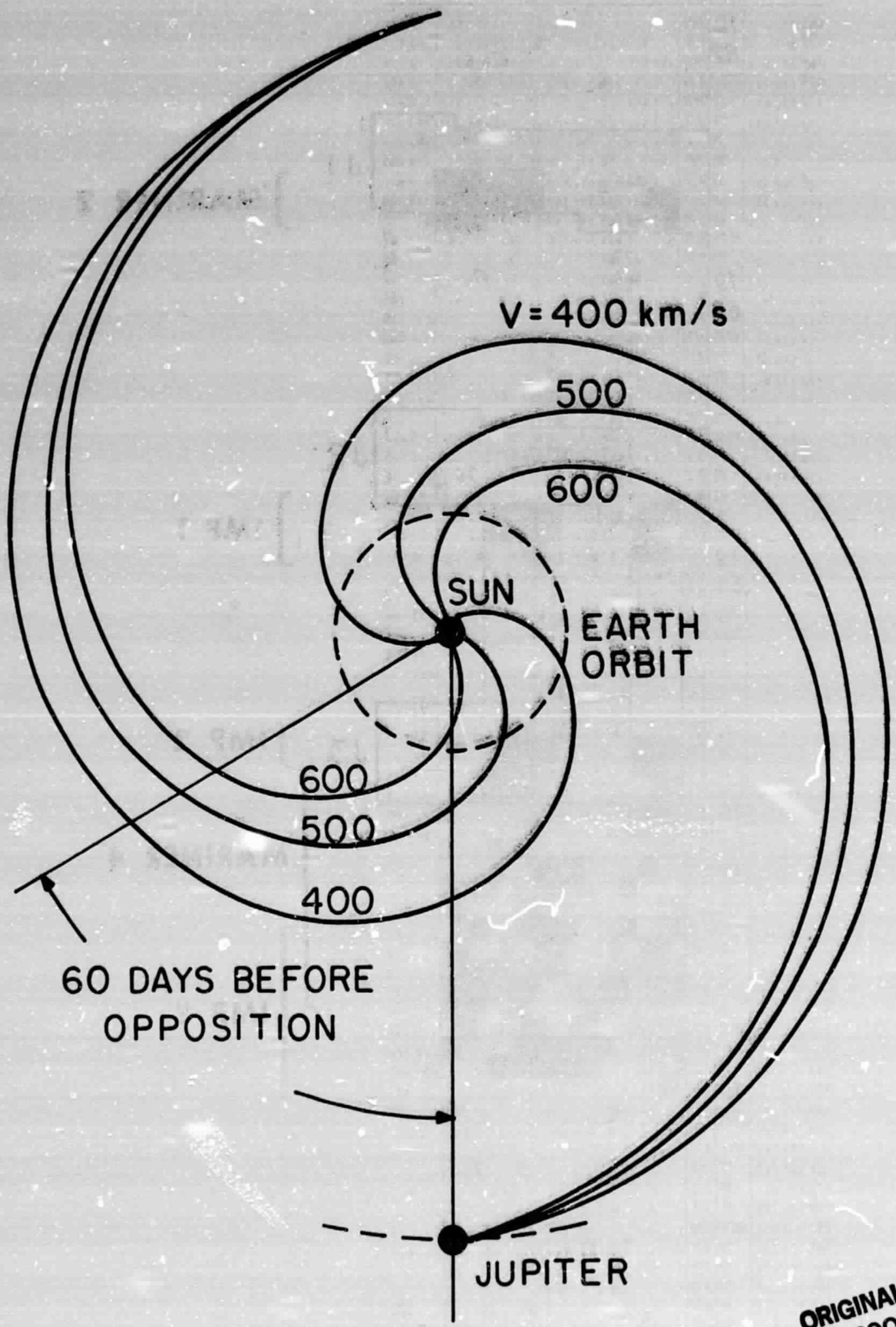

11.6
SUN
EARTH
JUPITER
24.3
(a)
V=300 km/s
18.2
SUN
5.4
EARTH
(b)
JUPITER
V=400 km/s
14.6
SUN
EARTH
1.9
(c)
JUPITER
V= 500 km/s
12.2
SUN
EARTH
JUPITER
24.9
(d)
V=600 km/s


V = 300 km/s
350
400
SUN
EARTH ORBIT
60 DAYS BEFORE OPPOSITION
JUPITER



BEFORE OPPOSITION
1962-1964 (275 EVENTS)
UCRAO SWEPT FREQUENCY
Ap
18
17
16
15
14
13
12
14
13
300
500
km/s
300
500
AFTER OPPOSITION
1962-1964 (141 EVENTS)
Ap
20
19
18
17
16
15
14
300
500
km/s
300
500
30
20
10
0
10
20
DAYS BEFORE EPOCH


R
Rot-Nr.
1st day
C9
1962
1963
1964
1965
1966
J1
J2
J3
MARINER 2
IMP 1
IMP 2
MARINER 4
IMP 3


V = 400 km/s
500
600
SUN
EARTH
ORBIT
600
500
400
60 DAYS BEFORE
OPPOSITION
JUPITER