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JUPITER'S DECAMETRIC RADIO EMISSION AND SOLAR ACTIVITY

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Abstract—The possibility of a short-term correlation between Jupiter's decametric radio emission and solar activity has been investigated for the 14 apparitions between 1960 and 1975. Artificial periodicities in the Jupiter data and other complicating factors are discussed, and it is found that the most serious periodicities liable to be present are Io-dependent. Using the geomagnetic A_p index as the indicator of solar activity, the Chree superposed epoch technique is applied to the Non-Io events, separated into two month periods before opposition and two month periods after opposition, as an additional test for correlation. While positive correlations appear from all of the data, without selection, the correlation is enhanced for Non-Io events and indicates a consistent picture of solar particles having velocities within the range 300–500 km s^{-1} activating some, if not all, of the Non-Io emission. In the before opposition case a secondary (negatively delayed) correlation peak, corresponding to particles travelling first to Jupiter and then, after almost a whole solar rotation, to Earth, predominates over the direct case. There is also a general tendency for values of the A_p index before opposition to increase before epoch and after opposition to decrease before epoch. The positive correlations are much enhanced for the three apparitions 1962–1964, during which period a well-defined repetitive pattern of solar activity occurred. There is little or no indication of correlation for Io-related events although an approximate eight day periodicity is apparent.

1. INTRODUCTION

The possibility of a short-term correlation, between Jupiter's decametric radio emission and various indicators of solar activity, has been investigated by a number of workers. In most of the studies, the general principle invoked has been that solar particles activate something at Jupiter which, directly or indirectly, causes the radio emission. Generally the approach has been to use either simple cross-correlation for short continuous periods of observation within a single apparition (for example, Carr *et al.*, 1960; Roberts, 1960; Barrow *et al.*, 1964; Conseil *et al.*, 1971; Kovalenko, 1971; Gruber, 1975) or, the Chree superposed epoch technique to combine the data from several apparitions (for example, Sastry, 1968; Barrow, 1972; Pokorný, 1976). The more recent studies have been well reviewed by Carr and Desch (1976), who discuss the conflicting results obtained, indicating, to some extent, anticorrelation, no solar influence, or positive correlation!

In a previous paper (Barrow, 1972, subsequently referred to as Paper I), the problem of possible short-term correlation was examined and the complicating factors were discussed. Using Jupiter events as epochs, the Chree analysis method was applied to Jupiter data taken from 1961 through 1968, events being selected by a criterion based upon duration and intensity. The data were separated into two parts; two month periods before each opposition and two month periods after each opposition. Solar activity was represented by the standardized geomagnetic character figure C_p and a correction was made for serial correlation in the geomagnetic data. Peaks, better than 1% significant, representing delays between periods of enhanced geomagnetic activity and Jupiter's more energetic events, were found in the superposed epoch tables. It was suggested, therefore, that at least some of the radio emission from Jupiter might be activated by solar particles. The peaks in the tables were centred on delays of about 12–13 days, in the case of the after opposition data, and about −9 days in the case of the before opposition data. In both cases, these correspond to a particle radial velocity of about 500 km s^{-1}. The negative delay was interpreted as being due to the case where particles first travelled towards Jupiter and then, after almost a whole solar rotation, reached Earth *after* Jupiter had been active. This, of course, implies a relatively long-lived solar feature and a correspondingly constant radial velocity for the effluxing solar particles.

It was pointed out in Paper I, and further commented upon by Carr and Desch (1976), that a peak, positively delayed by some 17 or 18 days due to the first passage of the solar wind stream across Earth, might also be expected in the before opposition case. However, this did not appear to be present.

The calculations for Paper I were restricted by the very limited computing facilities then available to the writer. This situation has now improved, however, and the whole problem has been re-examined, using the latest catalogue of Jupiter activity (Warwick *et al.*, 1975), published by the University of Colorado Radio Astronomy Observatory. This catalogue is available on magnetic tape and covers the 14 apparitions from January, 1960 through March, 1975.

Two approaches are possible. One can assemble a large amount of data and hope to see a significant trend from the massive statistics; or one can examine a shorter period, in which some clearly recognizable pattern of solar behaviour is known to be present, and hope to see this pattern superimposed, to some extent, upon the Jupiter data. Both approaches have been used in the present study.

2. COMPLICATING FACTORS

The complicating factors which might obscure a simple correlation were discussed in detail in Paper I. Briefly, these are: (a) Changing Earth–Sun–Jupiter geometry; (b) Range of velocities possible for the solar wind particles during each apparition, even if the velocities are approximately uniform and radial during shorter periods; (c) Possibility of the presence of both correlated and uncorrelated types of Jupiter radiation. This latter possibility now appears to be even more likely, as the findings of the recent Pioneer 10 and 11 missions (Van Allen, 1976) indicate that a considerable proportion, but not all, of the energetic particles in the Jovian magnetosphere may come from Jupiter's ionosphere, rather than from the solar wind. Artificial periodicities, and the distinction between Io-correlated and Non-Io correlated events are considered in Section 3.

The availability of intermittent periods of Jupiter data, as well as the case when Jupiter might be active but radiating in directions away from Earth, is overcome to a large extent by the use, following Sastry (1968) and Paper I, of Jupiter events as the epochs in the Chree analysis. Because of (c) above, we should expect any correlation that might exist to be superimposed upon a "background noise" to the Chree analysis, while (a) and (b) would cause delay values to appear as a range of values rather than as a single value.

It was shown in Paper I that the delay Δ, in days between the arrival of solar particles at Earth and at Jupiter is given, to a good approximation, by:

$$\Delta = \frac{d_J - d_E}{v_r} - \frac{\phi}{\Omega}, \qquad (1)$$

or

$$\Delta = \Delta_o - t_\phi. \qquad (2)$$

where d_E, d_J are, respectively, the mean distances from the Sun of Earth and of Jupiter, ϕ is the angle between the corresponding two emission directions of the particles and is taken as increasing positively after opposition, v_r is the radial velocity of the particles, Ω is the angular velocity of solar rotation, and Δ_o is the delay at opposition ($\phi = 0$). Thus a plot of Δ against t_ϕ will be linear and of slope -1, as shown in Fig. 1. The ranges of delays that might be expected for particle velocities of 300–500 km s^{-1} are shown by the shaded areas. These refer to separated two month periods before and after opposition. Typically, for the after opposition data, we might hope to find a peak in the Chree table corresponding to delays ranging from about 10 to 24 days, for a Jupiter event following an

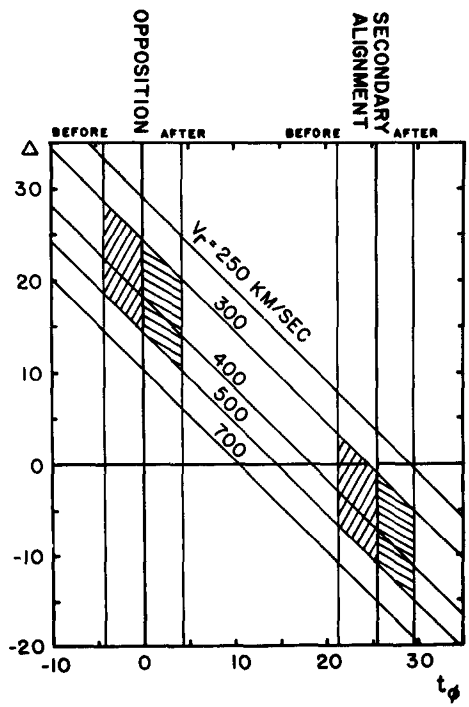

FIG. 1. DELAY TIME Δ IN DAYS AGAINST THE TIME t_ϕ IN DAYS FOR TYPICAL VALUES OF v_r IN km s^{-1}.

The shaded areas indicate the ranges of delay times to be expected before and after opposition for solar particle velocities of 300–500 km s^{-1}.

enhancement of geomagnetic activity. Two months periods are chosen, as in Paper I, as a reasonable compromise between significantly long data periods and peak broadening effects in the final results.

By separating the data into two parts, before and after opposition, an additional check on possible correlation is obtained from a comparison of the delays corresponding to the peaks in each of the two Chree tables.

It should be noted that, in principle, secondary peaks are possible in the analysis corresponding to

$$\Delta = (\Delta_0 \pm 25.4) - t_\phi, \tag{3}$$

where 25.4 days, the period of sidereal solar rotation, is the interval between successive arrivals of the same solar wind stream at Jupiter. These, however, are liable to be confused, if they occur at all, with the 27.3 day periodicity always present in geomagnetic indices.

3. PERIODICITIES

Sastry (1968), and Douglas and Bozyan (1970) have drawn attention to the presence of various periodicities in the Juptier data. Sastry has suggested that most apparent correlations may be explained in terms of these artificial periodicities. Much of the Jupiter activity is correlated with "source" longitude (λ_{III}) and with the geocentric longitude of Io (γ_{Io}). These introduce periodicities of $9^h\ 55^m\ 29^s\ 0.71$ and $42^h\ 28^m\ 35^s\ 0.95$ respectively. The availability of Jupiter observations, either from a single station or, from several stations grouped within a fairly narrow band of terrestrial longitude gives rise to a $23^h\ 56^m\ 04^s\ 0.09$ periodicity. Harmonics and beat periods may be expected to arise from these, having mean synodic periods T, given (Douglas and Bozyan, 1970) by

$$\frac{1}{T} = \frac{k}{T_J} + \frac{l}{T_E} + \frac{m}{T_{Io}} + \frac{n}{T_{Jsyn}} \tag{4}$$

where k, l, m, $n = 0, \pm 1, \pm 2 \ldots$ and T_J, T_E, T_{Io}, T_{Jsyn} are, respectively, the mean synodic periods of Jupiter's rotation, Earth's rotation, Io's revolution and Jupiter's year.

From Fig. 1, it is clear that, if a correlation should exist in accordance with the simple model proposed, then for typical solar wind velocities of 300–500 km s^{-1}, a range of delays might be expected for about 28–14 days in the before opposition case, and about 24–10 days in the after opposition case. If follows, therefore, that we are most concerned with periodicities of the same order. This is, conservatively, with frequencies between about 0.033 and 0.200 cycles day^{-1}, or periodicities of some 30–5 days.

By calculating the power spectrum for "theoretical occurrence probabilities" obtained from real data, Sastry (1968) has given the periodicities to be expected (his Fig. 4) within the range 0–0.5 cycles day^{-1}. The two most prominent periodicities within our present range of interest are, according to Sastry, those occurring at about 0.13 and 0.15 cycles day,$^{-1}$ or about 7.7 and 6.7 days, respectively. A check on possible Earth–Jupiter beat frequencies from Equation (4) over the ranges $|k| = 1-10$, $|l| = 1$–25, $m = n = 0$, indicates that both of these periodicities must involve Io as well as the rotation of Earth and Jupiter. In other words, they can only be given by Equation (4) for values of k, l, $m \neq 0$, if $n = 0$.

It is well known that if one attempts to predict Jupiter events using the Io effect (Merritt, 1965; Barrow, 1968), the A–C source predictions and the B source predictions tend to occur at adjacent seven-day intervals. The eight day cycle reported by Carr *et al.* (1960) is almost certainly a manifestation of this effect which is due to the fact that

$$17T_J \simeq 7T_E \simeq 4T_{Io}. \tag{5}$$

Thus, if a correlation analysis is confined to Non-Io related Jupiter events, we might hope to eliminate the most serious periodicities in the range of delays with which we are concerned.

Interactions between Earth and Jupiter alone (k, $l \neq 0$, $m = n = 0$) will certainly occur but, according to Sastry, these have lower spectral power. The frequency 0.18 cycles day^{-1}, corresponding to a period of 5.6 days, may be due to the condition $k = 2$, $l = 5$, $m = n = 0$, for example. Even so, with the different delay ranges anticipated from the before opposition and the after opposition analyses, it should be possible to distinguish real correlation from spurious periodicity by reference to equation (4), if only Non-Io events are involved.

Most indicators of solar activity contain a periodicity of about 27 days and some, including the geomagnetic indices, may contain further periodicities of less than 27 days. According to Ward (1960), the A_p index used in the present study, may contain periodicities given, in descending order of probability, by $27/N$ days where $N = 1$, 2, 3, 4, 5, 6. Ward's results suggest that the case $N = 2$ is often present, $N = 3$, 4 may sometimes be present, and $N = 5$, 6 are occasionally present for a finite number of solar rotations.

It is clear that, although much caution needs to be exercised in the assessment of correlation studies, it may still be possible to obtain a significant result if periodicities in the Jupiter data can be accounted for and distinguished in the final analysis.

4. ANALYSIS

4.1. *Massive statistics approach*

Chree analyses were conducted for the 14 apparitions during the period January 1, 1960 through March 21, 1975. All of the data listed in the University of Colorado Catalogue were considered for the two-month periods before and after opposition. Selection criteria, based upon the Io effect, were then incorporated into the programme. Solar activity was represented by the daily A_p geomagnetic index.

The statistical significances of the results were calculated, as in Paper I, following the method of Bell and Glazer (1957), from the standard error of the mean, modified to allow for serial correlation in the geomagnetic data and for soothing. The modified standard error σ_n' is then given by

$$\sigma_n' = \frac{\sigma}{\sqrt{N}} \sqrt{\frac{1}{n}\left[1+\frac{2(n-1)}{n}\rho_1+\frac{2(n-2)}{n}\rho_2\right]} \quad (6)$$

where σ is the standard deviation for the geomagnetic data, N is the number of epochs, ρ_1, ρ_2 are the auto-correlation coefficients for one and two day lags, respectively, and $n = 5$ for the running average involved in smoothing. Significance levels of 1 and 5 per cent are then given as usual by 2.58 σ_n' and 1.96 σ_n'.

This procedure has been used a number of times in the literature for various correlation studies involving solar activity indices. It is, strictly, applicable only to normally distributed data, however, while the geomagnetic index A_p is skewed somewhat towards lower values. The use of the standard error for the confidence levels is thus approximately valid but not exactly so.

Io-correlated events were separated from Non-Io events using the defining values for λ_{III} and λ_{Io}, given by Carr and Desch (1976) for their A, B, C and D sources. Here one encounters a problem, however. There are numerous events listed in all catalogues of Jupiter's radio emission which overlap one or more of the limiting values. How, for example, does one assess an event for which $\lambda_{III} = 207°–345°$ and $\gamma_{Io} = 254°–286°$? There does not appear to be any standardized policy published in the literature or, in fact, any reference to this point at all. While it is not difficult to establish arbitrary procedures for classifying events of this nature, it cannot alter the fact that some uncertain events will always be present in the selected data,* even if one hopes that the effect of these difficult cases will be relatively small.

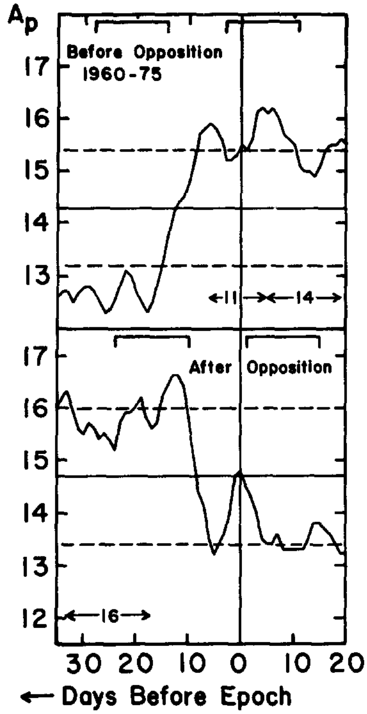

FIG. 2. CHREE ANALYSES OF JUPITER EVENTS AND GEOMAGNETIC INDEX A_p FOR THE 14 APPARITIONS DURING 1960–1975.

Upper section: 60 day periods before opposition, 560 events. Lower section: 60 day periods after opposition, 366 events. Broken lines indicate 1% significance levels.

In the present study, Non-Io events were defined by the exact limits given by Carr and Desch (1976) and these were selected from the catalogue. Both Io-correlated and "indeterminate" (overlapping) events were rejected, hopefully, to ensure that all Io dependent periodicities should be eliminated from the analysis. To avoid further confusion between Non-Io, "indeterminate," and Io-correlated activity, the analyses have been conducted by events rather than by days. They are thus weighted, to some extent, by days on which several events took place. Check runs on a day-by-day basis indicate that the general results are enhanced a little by this but otherwise unaffected.

The resulting smoothed and averaged superposed epoch diagrams are shown in Fig. 2. The upper

* The writer is pleased to acknowledge useful correspondence with Dr. T. D. Carr on this point.

section is the before opposition data and contains 560 events. The lower section is for the after opposition data and contains 366 events. The horizontal bars indicate the range of delays to be expected due to particle velocities in the range 300–500 km s^{-1}. In both the before opposition and the after opposition analyses, it can be seen that significant peaks occur within these ranges of delays. As in Paper I, however, it appears that before opposition, the secondary negatively delayed peak predominates over the direct case. If this latter is present at all it is certainly not statistically significant. Less significant peaks also appear above the one-per cent level and it is suggested that these are due to artificial periodicities in the data, as discussed in Section 3 and again in Section 5. Possible periodicities are indicated by arrows.

As an additional check, Chree analyses were conducted for (a) all of the Jupiter data without any selection; (b) the Io-correlated events, precisely defined by the exact limits given by Carr and Desch (1976); (c) the combination of exact Io-correlated events and indeterminate events, left over after the Non-Io events had been precisely selected for Fig. 2. One-per cent significant peaks appeared in case (a) and these were enhanced by the selection for Fig. 2. No unambiguous significant correlation appeared in either (b) or (c), although an approximate 8-day periodicity was apparent in all of these Io dependent cases, both before and after opposition.

4.2. *Limited period approach*

During 1962–1964, a well-defined repetitive pattern of solar activity persisted over a large number of solar rotations. The geomagnetic "musical scales" diagram showed this as several long-lived recurrent magnetic enhancements. These have been identified and studied by various workers (See, for example, Hakura, 1974) and they are catalogued in "Solar-Geophysical Data" (ESSA, U.S. Department of Commerce).

The Chree analyses, described in the previous section 4.1, were repeated for the three apparitions during 1962–1964, each apparition being examined separately and then combined. The results of the combined analysis are shown in Fig. 3. The upper section represents the before opposition data and contains 275 events. The lower section is the after opposition data and contains 141 events. It can be seen that the general features of the 1960–1975 study (Fig. 2) appear again but with considerable enhancement. Again, the principal peaks are within the horizontal bars of expected delays due to solar particle velocities within the range 300–500 km s^{-1}.

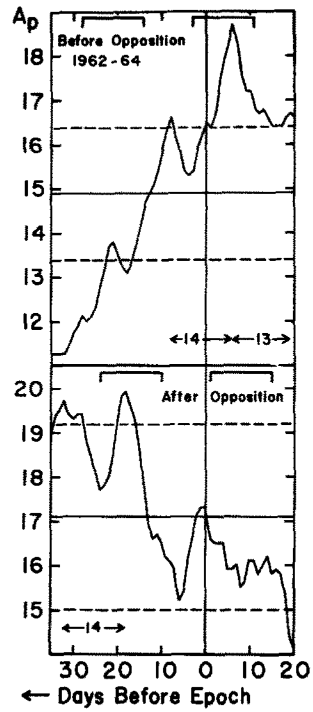

FIG. 3. CHREE ANALYSES OF JUPITER EVENTS AND GEOMAGNETIC INDEX A_p FOR THE THREE APARITIONS DURING 1962–1964.

Upper section: 60 day periods before opposition, 275 events. Lower section: 60 day periods after opposition, 141 events. Broken lines indicate 1% significance levels.

Again, it is suggested that these peaks represent real correlation, while the less prominent peaks above the significance level represent artificial periodicities which are indicated by arrows.

Check analyses were run as before, 4.1a,b,c; with similar results.

The principal features of Fig. 2 and 3 are summarized in Table 1. We note also that there is a general tendency for the values of A_p to increase sharply before epoch in the before opposition

TABLE 1. DAYS BEFORE EPOCH (Δ) ON WHICH 1% SIGNIFICANT PEAKS OCCUR, WITH CORRESPONDING IMPLIED VALUES OF SOLAR WIND PARTICLE VELOCITY (v_r) IN km s^{-1}

Before opposition				After opposition			
1960–1975		1962–1964		1960–1975		1962–1964	
Δ	v_r	Δ	v_r	Δ	v_r	Δ	v_r
6	1800	8	1200	33	210	32	215
−5	400	−6	420	(19)		18	365
				17*	380*		
−19	1700	−19	1700	(13)			

* See discussion under Section 5 (iii).

cases, and to decrease sharply before epoch in the after opposition cases.

5. DISCUSSION

It can be seen from Table 1 that the most prominent peaks in the Chree analyses correspond to reasonable solar wind velocities within the range 300-500 km s^{-1}. It is suggested, therefore, that solar wind particles, having radial velocities within this range, somehow activate much of the Non-Io Jupiter radiation. This result is consistent with measured values of the solar wind velocity subsequent to 1962, given by Gosling *et al.* (1971), and by Neugebauer (1975). The general results of the 1960-1975 analysis seem to be enhanced in the analysis for the three apparitions during 1962–1964, a period during which a well-defined repetitive pattern of geomagnetic activity implied the existence of unusually long-lived constant velocity particle streams. The activating process at Jupiter may be either direct or indirect and it may involve only a proportion of the Non-Io Jupiter events.

There are other peaks above the 1% significance level, however, which correspond to unlikely solar wind velocities, in excess of 1000 km s^{-1}, and lower values close to 200 km s^{-1}. It is suggested that these peaks may be due to artificial periodicities as follows:

(i) Periodicities of approximately 14 days are certainly present in three of the four analyses (Fig. 2, upper section and both sections of Fig. 3). There is also an approximate 13 day periodicity indicated in the upper section of Fig. 3. These may all be due to the case of $N = 2$ (that is a periodicity of about 13.5 days) in Ward's (1960) discussion of periodicities less than 27 days (in geomagnetic indices, outlined in Section 3.

(ii) An approximate 11 day periodicity is apparent in the upper section of Fig. 2. This may be a beat period between Ward's 13.5 day periodicity in (i) above, and the 5.6 day periodicity given by Sastry (1968) and suggested in Section 3 to be the case $k = 2$, $l = 5$, $m = n = 0$ in equation (4). These two give rise to a beat period of about 10 days.

(iii) the lower section of Fig. 2, the peaks centred on about 19 and 13 days before epoch might be regarded as separate, or they might be regarded as structures of a single peak centred on about 17 days before epoch. As both peaks correspond to solar wind velocities within the range 300–500 km s^{-1} the latter possibility is perhaps the more plausible; the more so as this interpretation would be consistent with the results of the other three analyses and, in particular, with the lower section of Fig. 3. A periodicity of about 16 days would then be implied, which is close to the condition $k = 5$, $l = 12$, $m = n = 0$, *in* equation (4), corresponding to a periodicity of about 17 days.

The most interesting question to arise is the predominance of the secondary peak in the before opposition analyses. A similar effect was observed in the previous study described in Paper I. In the present work, check runs using different selection criteria based upon intensity, frequency, and combinations of these with Non-Io events (for single apparitions, several apparations, and for all of the data for 1960–1975) all show the same general trend. The superposed epoch diagrams peak to the left of epoch in the after opposition data (as might be expected) but peak to the right of epoch (i.e. corresponding to a negative delay) in the before opposition data. In other words, peaks corresponding to long-lived solar activity, lasting for almost one complete solar rotation or more, seem to predominate over peaks that might be due to the much shorter solar rotation taking place over the range of Earth positions covered in the two month period before opposition. There is no obvious explanation of this effect, unless it is in some manner associated with the changing slope of the A_p background in Figs. 2 and 3. Possibly the Jupiter emission is triggered in some means by the conditions associated with a prolonged increase in geomagnetic index before opposition and by a prolonged decrease in geomagnetic index after opposition.*

There are, perhaps, further indications of the solar cycle in the data, especially if the analyses are extended beyond the present limits of 35 days before epoch to 20 days after epoch. These solar effects might be regarded as a means of distinguishing between real correlation and periodicities arising in the Jupiter data. Although, in this respect, they would tend to support the correlation, another problem is introduced in that extending the analysis limits too far can decrease the significance levels unrealistically. The present limits are chosen with this point in mind, as well as being wide enough to allow the main periodicities to be seen. In all four analyses the A_p background decreases immediately beyond both margins of Figs. 2 and 3.

Gruber (1975), using simple cross-correlation techniques, has suggested that an anti-correlation may be present between solar activity and Jupiter radiation for the seven apparitions during the

* I am grateful to the referee for drawing my attention to this point.

period 1960–1967, corresponding to delays of 5 days and, more probably, 27 days. In the present 1960–1975 analyses, there are certainly indications of a significant anti-correlation in the before opposition data associated with delays of about 18 or 26 days. The only corresponding feature in the after opposition analysis, however, is a very small peak corresponding to a positive delay of about 5 days which does not appear at all in the 1962–1964 analysis. By Gruber's own suggestion, a delay of 5 days seems unlikely to be real, as it implies such a high solar wind velocity. It is concluded, therefore, that in this respect the present results are at variance with those of Gruber, as are those presented in Paper I.

6. CONCLUSION

Chree analyses, for the 14 apparitions during 1960–1975, seem to indicate a consistent picture of Non-Io related Jupiter emission being activated in some manner by solar wind particles, having radial velocities in the range 300–500 km s^{-1}. It seems unlikely that this conclusion is due to artificial periodicities in the data. The most prominent of these latter, in the range of interest, also involve Io or can be accounted for.

The assumption is made throughout the paper, and in many other studies involving solar wind effects, that the solar wind velocity is radial, and constant for limited periods, out as far as the orbit of Jupiter. Also, that Earth vicinity measurements may be extrapolated out to Jupiter. As Carr and Desch (1976) point out, these assumptions may not be correct, although there is little information available on this point at present. Perhaps the positive correlations established in the present work at least imply that the solar wind behaviour follows a consistent pattern out to Jupiter. The enhancements for 1962–1964 seem to underline this and may even suggest that at times the assumption is better justified than previously expected.

An obvious refinement for future study would be to eliminate the possible effects of Earth rotation periodicity, by combining observations of Jupiter from several stations at widely separated terrestrial longitudes. The comprehensive catalogues published by Alexander (1970) and by Alexander, Kaiser and Vaughan (1975) would form a good basis for such a study.

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