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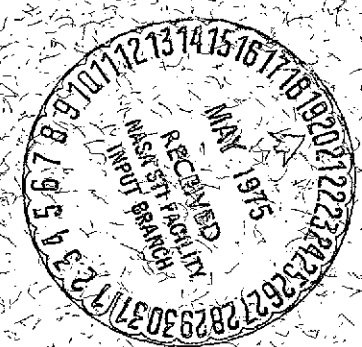

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INTERPLANETARY MAGNETIC FIELDS, THEIR FLUCTUATIONS, AND COSMIC RAY VARIATIONS

by

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Abstract

The cause of Forbush decreases is examined using neutron monitor data and measurements of the interplanetary magnetic field. It is found that for the period examined (Dec. 15, 1965 to April 23, 1966) large enhancements of the interplanetary magnetic field correlate well with decreases in cosmic ray intensity, while various parameters connected with the fluctuations in the field do not display such good correlation. The inference is drawn that Forbush decreases are not related to the turbulence or random motions in the field but to the large scale features of the field.

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Introduction

Among the many observational features of cosmic ray variations which a theory of cosmic ray propagation should explain, Forbush and similar decreases at neutron monitor energies appear to be conceptually the simplest. The eleven-year modulation may well have its cause in some region of space inaccessible as yet to observation, and solar flare events have the possible complication of the influence of the acceleration process or solar conditions.

One of the problems to be solved in the theory of Forbush decreases is the isolation of the specific factor in the interplanetary medium which is causing the phenomenon. In the recent review article by Lockwood (1971) a number of possible causative agents of Forbush decreases are discussed and the merits of each model are shown. Barouch and Burlaga (1975) have argued the case for regions of high magnetic field, ("blobs") being the main cause; however, because of the well-known association of high fields with disturbed conditions, they were unable to demonstrate unambiguously that the strength of the field, rather than the amplitude of the fluctuations, was causing the decreases. Many workers in this field still attribute considerable importance to scattering by the small-scale magnetic fluctuations, although Parker (1963) had made the point that this required unreasonably large values of the field strength. It is the purpose of this paper to examine the experimental evidence which may resolve this problem.

Analysis

To find the relationship between the cosmic ray intensity and the magnetic fluctuations, one needs to clarify two points. (a) What is the appropriate measure of the fluctuations? (b) Can local measurements of this quantity be adequately representative of conditions encountered along the cosmic rays' trajectories?

(a) Current theories of charged particle propagation in random magnetic fields (Jokipii, 1966, 1968a, 1971; Roelof, 1966; Hall and Sturrock, 1967; Hasselmann and Wibberenz, 1968; Kulsrud and Pearce, 1969) relate the diffusion coefficient of cosmic ray particles to the value of the power spectrum of the fluctuations at wave-numbers depending on the pitch-angle and gyroradius of the charged particles. This relation has been tested by comparison with experimental data by Gloeckler and Jokipii (1966) and Jokipii (1968b) at high energies (> 500 MeV/nucleon). In their analysis, the rigidity dependence of solar cycle cosmic-ray modulation was found to agree with theoretical predictions. Sari (1975) has shown that short term variations of the low-energy (40-80 MeV) galactic cosmic ray intensity, on the time scale of a few days, follow the variations of the calculated modulation parameter V_w/K_{rr}. This parameter, the solar wind speed divided by the radial diffusion coefficient, was related to a perturbation solution of the Fokker-Planck equation governing the propagation of low-energy cosmic rays.

(b) The time scale appropriate for the study of Forbush decreases is about a day. During that time, a spacecraft will measure the magnetic field over a perpendicular distance $\ell = V_\omega t \sin \phi \cong 2\text{-}3.10^7$ Km, where ϕ is the angle between the solar wind speed and the average field.

The distance d over which cosmic ray will diffuse is $(K_\perp t)^{\frac{1}{2}}$, where $K_\perp$ is the perpendicular diffusion coefficient. For the cosmic rays in the energy range studied by Sari, $K_\perp \leq 10^{20}$ cm^2/sec, so that $d \cong 3.10^7$ Km, i.e. $d \cong \ell$. For cosmic rays of neutron monitor energies, $K_\perp = 10^{21}$ cm^2/sec, so that $d \cong 5\ell$. Thus, it may appear that for the energy range $\geq$ 500 MeV, the magnetic field observed by a spacecraft is only a fraction of the distance sampled by the cosmic rays. This is tempered by an observation which has two consequences. It has been shown that Forbush decreases are associated with blobs of high field intensity extending over a considerable region of space. Within these regions, where the field is, say, three times as high, the radius of gyration is three times smaller and the perpendicular diffusion coefficient may be reduced, assuming that the field random walk remains constant (Jokipii, 1969; Klimas and Sandri, 1971). Thus, during Forbush decreases one can anticipate that the magnetic field sampled by a spacecraft is representative of conditions observed by the cosmic rays. One probably cannot extend this conclusion to cosmic ray variations during quiet times, for which daily estimates of V_w/K_{rr} may not be the appropriate parameter to study.

On the other hand, except for the 11-year modulation the most significant variations in the high-energy cosmic-ray counting rates (of the order of a few percent) are the Forbush decreases and associated recoveries. If local irregularities in the magnetic field, other than shock waves or discontinuities, are at all associated with Forbush decreases effects, one can reasonably expect to observe correspondingly significant variations in the predicted propagation parameters at such times, even though correlations with quiet time conditions may be unobservable. If indeed magnetic fluctuations are associated with Forbush decreases, the following effects should occur:

1) K_{rr} should decrease at such times

2) V_ω/K_{rr} should increase at such times.

Data

The cosmic-ray data for this study were obtained by the Sulfur-Mountain neutron monitor and consists of daily averages of the corrected counting rates. The magnetic field and solar wind data were obtained from the results of Pioneer 6 experiments (Ness et al., 1966; Lazarus et al., 1966) from December 17, 1965 to April 23, 1966. Daily averages of the solar wind speed are used, with a statistical, standard deviation of generally less than 7% of the average bulk speed of 4×10^7 cm/sec. Over the interval with which we are concerned, Pioneer 6 traveled from a heliocentric radius of 1 AU to 0.81 AU with an Earth-sun-Pioneer angle varying from between -1 to $+4^\circ$. The separations between spacecraft and earth should not be signfficant since an ideal magnetic field line transported by the solar wind in the average Archimedes spiral will reach earth less than half a day after reaching Pioneer 6.

In order to estimate the propagation parameters, we employ Jokipii's (1966, 1968b) derivation of the diffusion coefficients for propagation parallel to the average interplanetary magnetic field, (slab model).

$$K_{\parallel}(R) = 2\alpha(\alpha+2)\, c\, \beta\, R^2/9V_w\, P_{xx}(f = V_w \bar{B}/2\pi R) \qquad (1)$$

Here $R = pc/ze$ is the particle's rigidity, $\beta = v/c$, V_w is the solar wind speed, and $\bar{B}$ is the average magnetic field strength. $P_{xx}(f)$ is the power spectrum of the magnetic field fluctuations at frequency f, perpendicular to the average magnetic field direction (B_z) and the spectra are calculated for positive frequencies only, leading to the factor of two difference with Jokipii's (1966) formula.

For frequencies less than 10^{-4} Hz the spectra are generally constant, and at higher frequencies they vary as $P_{xx} = Af^{-\alpha}$, $1 < \alpha < 2$. For our case the cutoff rigidity of the Sulfur Mountain neutron monitor is approximately 1 GV. Since this rigidity roughly corresponds to the peak of the cosmic-ray energy spectrum, this will also represent a large majority of particles being detected. Based on Jokipii's (1966) work, the particles should then be responding to frequencies greater than 10^{-4} Hz, a region which is generally well represented by power law spectra.

In the observer's frame of reference $K_{\parallel}$ should be a reasonable estimate of K_{rr}. This results from the fact that if, as expected, $K_{\perp} \ll K_{\parallel}$, then, $K_{rr} = K_{\parallel} \cos^2\Psi \simeq K_{\parallel} \cos^2\Psi$, in the frame of the solar wind. Further, if the fluctuations in the field other than discontinuities are basically Alfvènic with their $\vec{k}$ vectors oriented along $\vec{B}$ (Daily, 1973), the measured $K_{\parallel}$ will be approximately equal to K_{rr} for power spectrum slopes on the order of $\alpha = 2$ (for details see Sari, 1975).

In order to compute $K_{\parallel}$, least square fits to the magnitude and slopes of daily power spectra of the magnetic field were utilized, where the spectra were computed by the methods of Blackman and Tukey (1958) in a field aligned system. The spectra covered the frequency range of 1.4×10^{-4} to 1.7×10^{-2} Hz and were computed at an equivalent of 40 degrees of freedom when all data for 24 hours was present (Sari, 1972, 1975). Since P_{xx} and P_{yy} are not always equal, $K_{\parallel}$ was set equal to the average of K_{xx} and K_{yy} as computed from P_{xx} and P_{yy}.

A little thought must be given regarding the validity of equation (1). There is presently controversy as to the correct expression for $K_{\parallel}$

depending on the statistical properties of the random magnetic field and the ratio of the cosmic-ray gyroradius to the correlation length of the magnetic field (Klimas and Sandri, 1971, 1973; Jokipii, 1972; Jones et al., 1973; Kaiser et al., 1973). For large gyroradii and isotropic field fluctuations $K_{\parallel}$ should depend on the power spectra at zero frequency (Jokipii, 1971). The gyroradius of the particles with which we are concerned is $\approx 10^{11}$ cm in the average field and perhaps three times less in the enhanced field. This gyroradius is on the same order as the correlation length appropriate for high energy particles (Jokipii and Coleman, 1968; Fisk and Sari, 1973). (Using a different definition for the correlation length, Hedgecock (1975) obtains correlation lengths five times larger). Thus, we should not be in the large correlation length regime. In any case, it is difficult to estimate the zero frequency power on a day-to-day basis.

In the limit of small gyroradii and isotropic field fluctuations a simple, analytic formula for $K_{\parallel}$ may not exist (Goldstein et al., 1975). Equation (1), however, should be valid for all gyroradii for magnetic fluctuations depending only on the average field direction (slab model).

Results

In Figure 1 we plot daily averages of the Sulfur Mountain counting rate, V_w and $\bar{B}$ and the computed values of $K_\parallel$ and $V_w/K_\parallel$ for the period December 17, 1965 through April 23, 1966. Days for which there was insufficient magnetic data to calculate power spectra at greater than 15 equivalent degrees of freedom in the frequency range of 1.4×10^{-4} - 1.7×10^{-2} Hz were not used, on the basis that the spectral estimates might be unreliable. However, the average magnetic field values for such days may still be plotted.

One can draw some interesting conclusions from Figure 1. First, note that times of small Forbush (or Forbush-like) decreases, such as January 24, February 11, February 19, March 2, March 8 and March 12 are generally associated with high magnetic field values, as was observed at a different time period by Barouch and Burlaga (1975). At the times of these decreases, however, expected similar decreases in $K_\parallel$ or increases in $V_w/K_\parallel$, which would indicate increased scattering, are not generally present. In fact, for the largest Forbush decrease, around March 25, $K_\parallel$ is seen to increase rather than to decrease. This increase in $K_\parallel$ at March 25 is partly due to relatively constant, although high, magnetic field values.

Although it is possible that some of the smaller decreases may have resulted from increased cosmic-ray scattering and more limited access along tubes of flux intersecting the earth, the predicted propagation parameters do not indicate increased scattering for the largest and most clearly significant Forbush decrease. While the large Forbush

decrease may have resulted from a shock wave or tangential discontinuity, the contribution of such magnetic field structures will be included in the computation of the power spectra but must be limited when taken with a whole day's data. Certainly increased magnetic field fluctuations over a large local area are not noted with the March 25 decrease. The only phenomenon consistently observed with all of the above decreases is the occurrence of high magnetic field strengths.

Another way of checking how cosmic ray changes are related to B, $K_{\parallel}$ or $V_w/K_{\parallel}$ is to calculate the correlations between Δj and these variables. We chose as a measure of the change in some quantity X the estimate $\Delta Xi = (X_{i+1} - X_{i-1})/X_i$. This is an approximation to the logarithmic differential, and is conveniently dimensionless. One expects the magnitude and radial gradient of $K_{\parallel}$ and $V_w/K_{\parallel}$ to set the average level of the cosmic ray intensity j, while fluctuations in these quantities could correlate with transient changes in j. Thus, the correlations to establish are between the changes in these quantities and the change in j. We have a fairly small number of data points, and their values fluctuate quite a bit. Consequently one expects the correlation coefficient to have a relatively large error. By looking at the variation of the correlation coefficient with the lag (this is an approximation of the cross-correlation function) we can hope to see trends which, although not statistically independent, will give us more confidence in our conclusions. We have not included small values of Δj (less than 0.15%) in our calculations since their significance is unclear.

Figures 2a-2e present the calculated correlation coefficients as a

function of the lag for the variables discussed and for the wind speed as well. The only well defined trends are in the correlations between Δj and B, ΔB, and ΔV_w. For the parameters calculated from the diffusion theory, the correlation coefficients are much smaller, exhibit no trend, and are often of the wrong sign.

Although cosmic-ray scattering as predicted from formulations of parallel diffusion do not correlate with the Forbush decreases, it should be noted that this discussion does not exclude the possibility of a correlation with decreased transverse diffusion into regions of magnetic "blobs". Such a suggestion was proposed by McCracken et al., (1966) in a study of Forbush decreases observed by Pioneer 6. Theoretical predictions of the perpendicular diffusion coefficient (Jokipii, 1971) depend however on estimates of the magnetic field power spectrum at zero frequency. As mentioned above, such estimates are difficult to obtain for short data periods and thus transverse diffusion is not treated here.

Conclusions

Although our data are not very extensive, we feel that they are sufficient to show that a straightforward application of the results of contemporary cosmic ray propagation theory to the problem of Forbush decreases is unsatisfactory. The hypothesis that the origin of Forbush decreases is the regions of high magnetic fields is found to be in qualitative agreement with the data over the period analysed. It is hazardous to guess whether an adaptation of the diffusion type theory to the Forbush decrease phenomenon can be successfully realized. On the other hand, most of the power spectra of the interplanetary magnetic field which have been applied in this theory were obtained at about 1 AU. Forbush decreases are short-lived, localized phenomena, and theory should be able to predict the characteristics of these events on the basis of local field measurements. In the present state of the diffusion theory this is not the case.

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Figure Captions

Figure 1 Daily values.

Figure 2 Correlation coefficient as a function of time lag in days between the variation in cosmic ray intensity at Sulfur Mountain and (a) the variations in solar wind velocity, (b) the variation is computed diffusion coefficient, (c) the variation is magnetic field intensity, (d) the variation is modulation parameter, (e) the field intensity.

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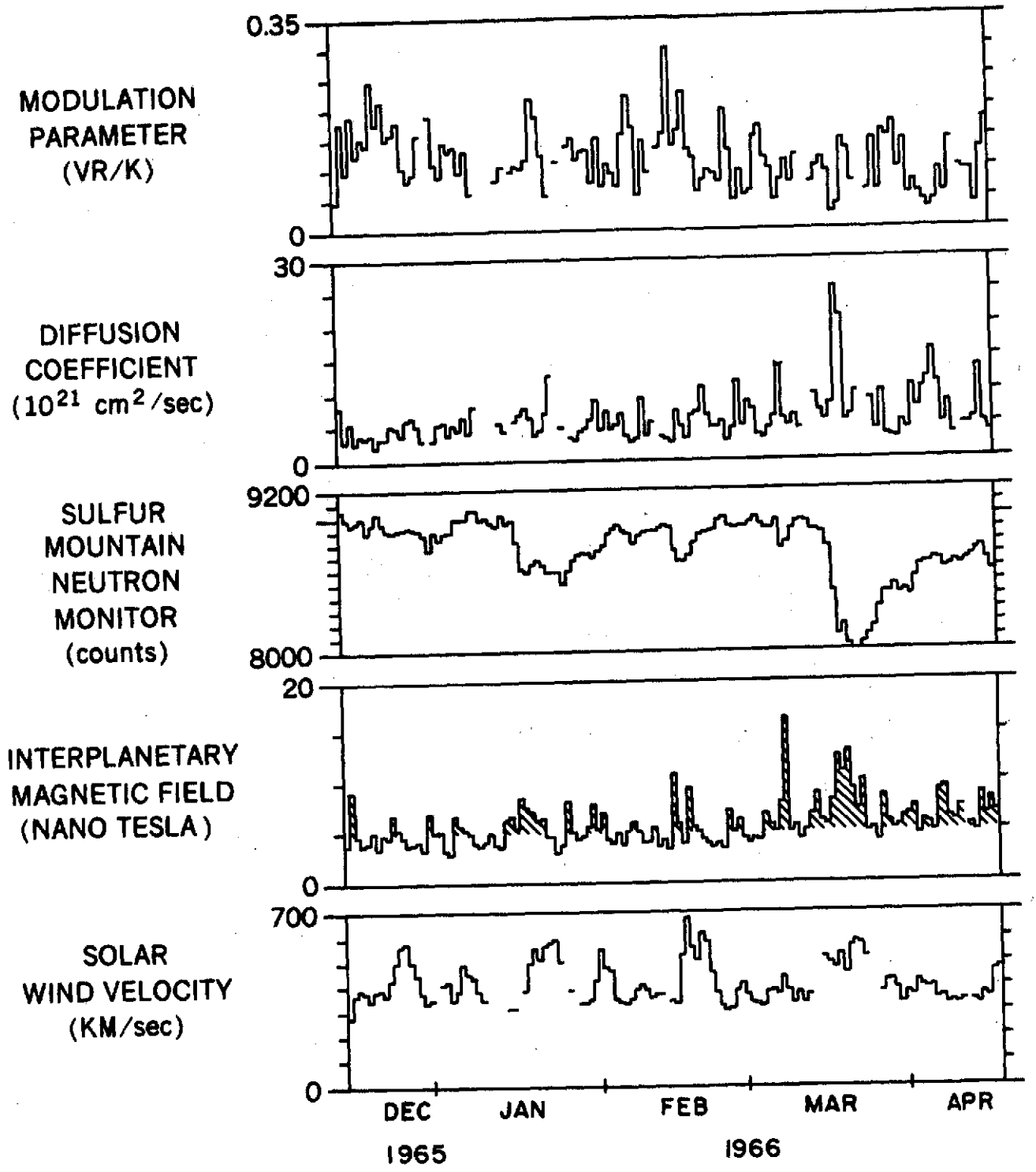
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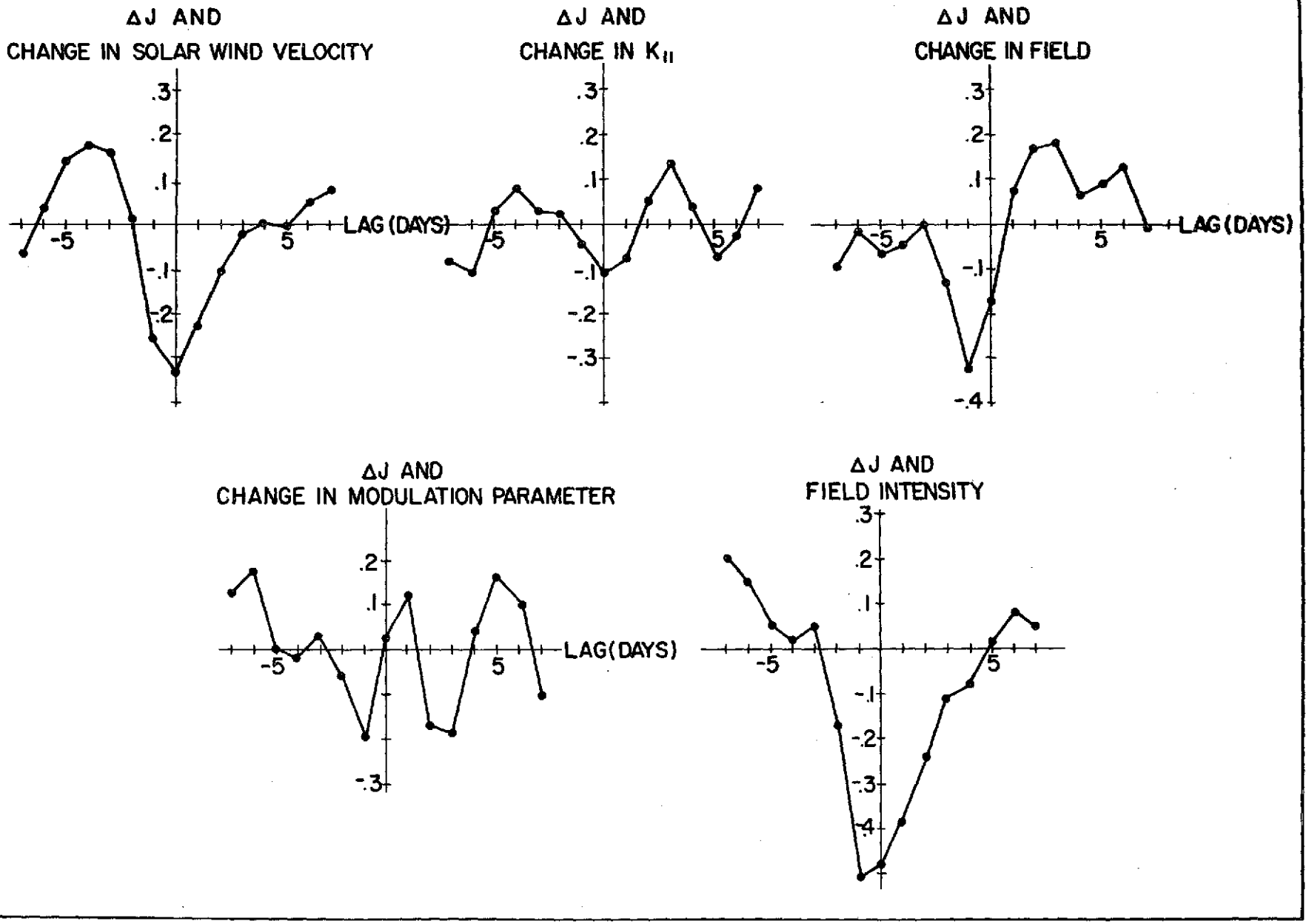
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