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THE MODULATION OF LOW ENERGY GALACTIC COSMIC RAYS OVER SOLAR MAXIMUM (CYCLE 20)

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This note is a preliminary report on detailed observations of low energy (~ 60 MeV/nucleon) galactic cosmic rays made during the recent period of solar maximum. For this particular cycle a significant time lag between intensity changes in the low energy and high energy components has been observed. There are a number of possible explanations of this "hysteresis effect". In the simplest form these include either changes in the form of the magnetic field power spectrum or changes in the size of the effective modulating region, or both.

The time histories of the 60 MeV/nuc galactic protons and alpha particles and of the high energy component as represented by the Deep River Neutron Monitor rates, for the period June 1967 - October 1971, are shown in Fig. 1. The low energy data was obtained from the GSFC cosmic ray experiments flown on the IMP IV and V satellites. Special care was taken to insure there was no solar particle contamination in the 40-80 MeV/nuc energy interval. This was done by examining the spectra over the complete 4-80 MeV interval and selecting only those periods where the 4-30 MeV flux was low and characterized by a steeply falling energy spectrum.

Examination of Fig. 1 shows that the low energy components and the neutron monitor rates display the same trends from 1967 to mid-1970. However, by early 1971 the Deep River Neutron Monitor rate has returned to its 1967 level while the 60 MeV/nuc proton and alpha particle intensities have just begun to show significant increases. A similar behavior has previously been observed for 0.02 - 20 GeV electrons (Meyer et al 1971) and for 1 - 10 MeV secondaries neutrons (Verschell et al 1971).

This "hysteresis effect" is more clearly defined by plotting the 60 MeV/nucleon protons and alphas versus the Deep River Neutron Monitor counting rate on a semi-logarithmic scale (Fig. 2a and b). It is seen that the proton data can be fitted by two essentially straight and parallel lines. The top line covers the period from mid-1965 to late 1969 and the lower parallel line covers the period July 1970 to September 1971. The alphas (Fig. 2b) display an almost identical behavior except that the displacement of the two parallel lines at a given Deep River rate corresponds to a factor of 2 change in alpha flux compared with a factor of 2.6 for the protons (Fig. 2a). The period from late 1969 to July 1970 is one of transition with the data suggesting that the alphas "lead" the protons. Earl and Rygg (private communication) observed only a factor of ~ 1.04 for protons above 750 MeV. These results show that there is a well defined hysteresis in solar cycle 20 and that this effect is strongly rigidity dependent. They also confirm the preliminary reports given independently by Van Hollebeke et al. (1972), Garcia-Munoz et al. (1972), and Lockwood et al. (1972).

The question then arises as to whether the phenomena we report here is a characteristic feature of each solar cycle or is unique to cycle 20. For the maximum of the solar cycle 19, Simpson (1963) reported a significant hysteresis during 1954-1962 between neutron monitor rates at Chicago and Climax (vertical cutoff rigidity of ~ 1.3 GV and ~ 3 GV respectively) and at Huancayo (vertical cutoff rigidity ~ 13 GV). However, this was reduced to almost negligible proportions when corrections due to the drift in the Huancayo aneroid pressure gauge were made (Simpson and Wang, 1970). From a regression plot of the low-energy data obtained from polar, high altitude observations (Neher, 1971), and Mt. Washington neutron monitor rates, Webber (1967) found no evidence for hysteresis over cycle 19. Thus in our sample of 2 solar maxima, we find one displaying a well defined hysteresis extending up to energies of several hundred MeV and an apparent absence in the previous cycle. In this regard, it is interesting to note that during cycle 19, the sunspot number peaked at a value of ~ 200 for only 6 months, while during cycle 20, it stayed at a maximum value of 105 for almost 3 years.

On the other hand, by comparing the data from Geiger counter arrays on IMPs I, II, and III (protons $\geq$ 60 MeV, electrons $\geq$ 3 MeV) and the Deep River Neutron Monitor rates for the 1963-1966 period, Balasubrahmanyan et al. (1968) found a well defined hysteresis effect over the last solar minimum. These results were confirmed by Kane and Winckler (1969) using ion chamber measurements (protons and alphas $\geq$ 12 MeV/nuc, electrons $\geq$ 0.6 MeV) on OGOs I and III satellites. However, in a compilation of differential spectrum measurements from several different experiments, O'Gallagher (1969) discussed the previous results and report a negligeable effect over the same period. A further analysis of this part of the solar cycle should be made to resolve this discrepancy.

The shapes of the low-energy cosmic proton and alpha spectra measured at solar minimum have been accounted for by Goldstein et al. (1970) using a numerical solution (Fisk, 1971) to the spherically-symmetric Fokker-Planck equation which allows for the effects of convection, diffusion and energy loss. Their results are consistent with an interstellar differential spectrum proportional to $(T_o + T)^{-2.65}$, where T_o is the particle rest mass energy and T the kinetic energy.

The Fokker-Planck equation is given by (Parker, 1965; Gleeson and Axford, 1967)

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2VU)-\frac{1}{3}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2V)\right)\frac{\partial}{\partial T}(\alpha TU)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial U}{\partial r}\right) \qquad (1)$$

$U(T,r,t)$ = cosmic-ray number density at time t and radial distance r from the sun

V = solar wind speed

α = $\frac{T+2T_o}{T+T_o}$

$\kappa(\beta,P,r,t)$ = particle diffusion coefficient,

β = particle speed in units of c

P = particle magnetic rigidity

We find that to theoretically reproduce from the above equation the observed proton and alpha differential energy spectra, as well as the hysteresis effect over a solar cycle, it appears necessary to change either the rigidity dependence of κ, or the size of the modulation region as a function of time or both of these. In Table I we give two possible forms of κ. These differ slightly from the one used by Goldstein et al. (1970). The form $\kappa\alpha$ constant in r in the inner solar system has recently been advocated by Fisk et al. (1972).

The values shown in Table I for $A(t)$ and $\gamma(t)$ for case I, and $m(t)$ for case II, are used with the interstellar proton and alpha differential energy spectra of Goldstein et al. (1970) to produce the dashed curves in Figs. 2a and 2b. These parameters are changed smoothly over the indicated range for a given period. We emphasize that neither of these cases or the choice of parameters are unique and that both cases can be made to produce identical results by the proper choice of parameters. For example, in case I we could vary D instead of A. Furthermore, we could also consider a combination of cases I and II. Other possible ways of producing a hysteresis effect by changing the rigidity dependence of κ have been pointed out by Nagashima et al. (1966) and by Urch and Gleeson (1972).

It is interesting to note that in case I, $\gamma(t)$ changes only from 1.0 to 1.2. According to Jokipii (1966), this corresponds to a decrease on the order of 20% in the index of the magnetic field power spectrum. This would appear to be more physically reasonable than the large changes required in D(t) in case II. However the suggestion that the alpha particles lead the proton in the transition period, making the lag time shorter for high rigidity, seems to favor a model depending on the size of the modulating region. The radial cosmic-ray intensity gradients predicted by these two cases are somewhat different. For example, the intensity gradient of ~ 60 MeV protons during late 1971 for case I and II are ~ 95%/A.U. and ~ 62%/A.U. respectively.

The fact that such a well defined hysteresis is observed over solar maximum in cycle 20 implies changes in the state of the interplanetary medium. Magnetic field power spectra over this interval are not yet available. Examination of some parameters such as the solar wind speed and plasma ion density have been made over most of this period. It has been shown (Gosling et al. 1971) that the average plasma speed V remains approximately constant in time around a value of 400 km/sec. However, the 27 day averages plot of V shows a slight maximum of ~ 20% above this mean value during the period from late 1967-1968 (Montgomery and Bame, 1972). As it can be seen in Figure 2 this small change during this period cannot produce the observed hysteresis but it could be one of the factors affecting the power spectrum of magnetic field fluctuation making κ_o (Table I) smaller. Further, since the condition for hydromagnetic instabilities (which presumably generate magnetic field irregularities) to occur depends strongly on the ion plasma density (Burlaga, 1971, Davidson, 1972), this plasma parameter was also examined. The smoothed average plasma ion density was available during the period 1967 - July 1970 from Vela 4, Pioneer VI and Vela 5 (Bame, Private communication). During June 1967 - May 1969 the data show a small positive correlation between n and the 60 MeV proton intensity; n decreases by 20% while the proton intensity decreases by a factor of 2. During the transition period there is a break in the correlation. However the absence of data during the recovery period does not allow us to comment on the reality of this effect. Further measurements of ion plasma density during the decreasing phase of the solar activity, magnetic field power spectra over the solar maximum and the cosmic ray intensity gradients provided by Pioneer 10, should soon be available and provide a more definite clue to the process of the cosmic ray modulation.

Figure Captions

Fig. 1 - Time history of the 60 MeV/nuc cosmic ray protons and alpha particles for the 1967-1971 period. The upper curve is the Deep River Neutron Monitor rate averaged over the same interval as the corresponding alpha and proton measurements. The vertical lines mark the maximum and minimum neutron monitor rates during a given interval. The 1965 60 MeV proton level is derived from Kinsey (1970).

Fig. 2 - 60 MeV/nuc proton (a) and Alpha (b) data from Fig. 1 plotted as a function of the corresponding Deep River Neutron Monitor rate. The dashed line is the theoretical fit obtained for both model I and model II using the parameters listed in Table I. The indicated symbols divide the data into 5 different time periods.

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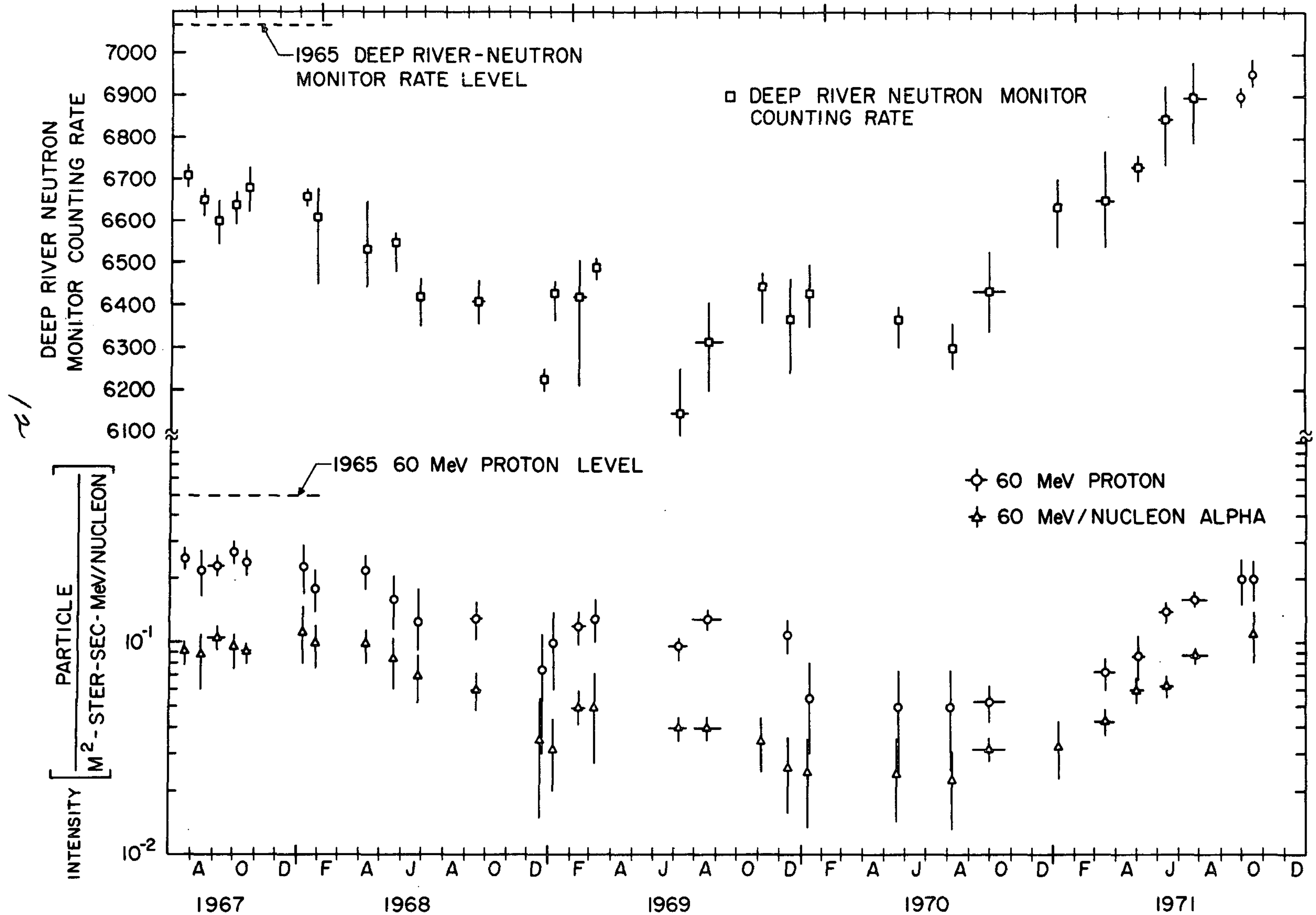
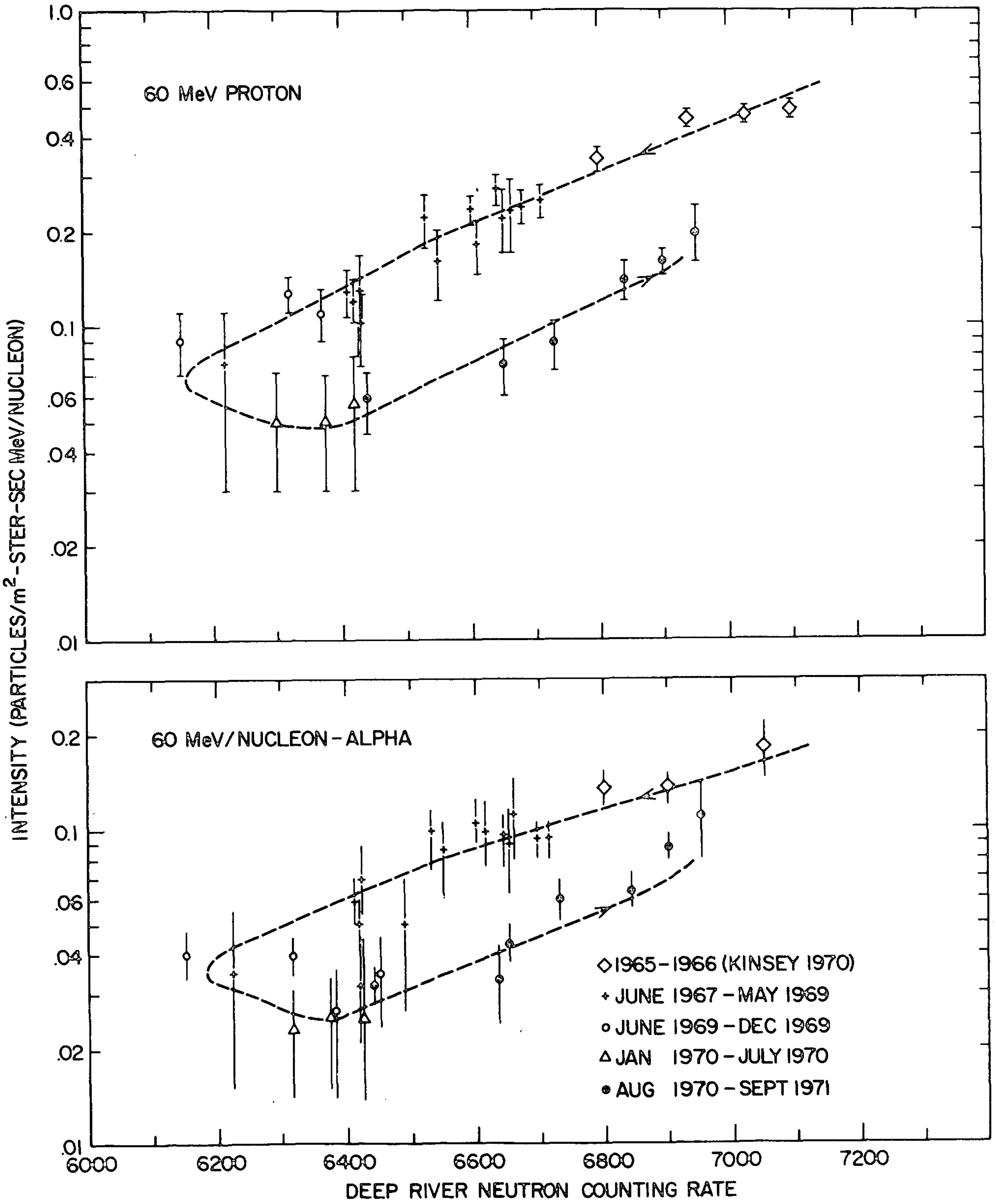
TABLE I. Two Representative Forms of $\kappa(\beta, P, r, t)$

Period	Case I: Change in rigidity dependence of κ		Case II: Change in the effective size of the modulation region		
	$\kappa(\beta,P,r,t) = \beta\kappa_o(r,t)\ P^{\gamma(t)}$ $\kappa_o(r,t) = A(t) \quad r \le D$ $D = 2$ A.U. $\kappa_o(r,t) = A(t)\mathrm{Exp}(\frac{r-D}{1.6}) \quad r > D$		$\kappa(\beta,P,r,t) = \beta\kappa_o(P,r,t)P$ $\kappa_o(P,r,t) = A(t) \quad r \le D(P,t)$ $\kappa_o(P,r,t) = A(t)\mathrm{Exp}(\frac{r-D}{1.6}) \quad r > D(P,t)$ $D(P,t) = 2(\frac{100}{P})^{1/m(t)}$		
	$\gamma(t)$	$A(t)\times10^{-21}$ (unit depends on $\gamma(t)$)	$m(t)$	$A(t)\times10^{-21}$ (cm^2/sec-GV)	D(t) for 60 MeV Proton (A.U.)
1965-1966	1.	1.5-1.12	∞	1.5-1.12	2
1967	1.	1.12-0.9	∞	1.12-0.9	2
1968-Dec.1969	1-1.06	0.9 - 0.6	$\infty \to 6$	0.9-1.12	2-5
Jan.1970-July 1970	1.06-1.2	0.6	6-3	1.12-1.8	5-13
Aug.1970-Sept.1971	1.2-1.1	0.6 - 1.0	3-4	1.8 - 2.7	13-8



1965 DEEP RIVER-NEUTRON MONITOR RATE LEVEL
DEEP RIVER NEUTRON MONITOR COUNTING RATE
1965 60 MeV PROTON LEVEL
60 MeV PROTON
60 MeV/NUCLEON ALPHA
DEEP RIVER NEUTRON MONITOR COUNTING RATE
INTENSITY [PARTICLE / M2-STER-SEC-MeV/NUCLEON]
7000
6900
6800
6700
6600
6500
6400
6300
6200
6100
10^{-1}
10^{-2}
A O D F A J A O D F A J A O D F A J A O D F A J A O D
1967
1968
1969
1970
1971

Fig. 1



60 MeV PROTON
60 MeV/NUCLEON - ALPHA
INTENSITY (PARTICLES/m2-STER-SEC MeV/NUCLEON)
DEEP RIVER NEUTRON COUNTING RATE
1.0
0.6
0.4
0.2
0.1
.06
.04
.02
.01
6000
6200
6400
6600
6800
7000
7200
◇ 1965-1966 (KINSEY 1970)
+ JUNE 1967 - MAY 1969
○ JUNE 1969 - DEC 1969
△ JAN 1970 - JULY 1970
● AUG 1970 - SEPT 1971

Fig. 2