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THE ACCELERATION AND PROPAGATION OF SOLAR COSMIC RAYS AS DEDUCED FROM THE RELATIVE ABUNDANCE OF PROTONS TO HELIUM NUCLEI

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THE ACCELERATION AND PROPAGATION OF SOLAR COSMIC RAYS AS DEDUCED FROM THE RELATIVE ABUNDANCE OF PROTONS TO HELIUM NUCLEI

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ABSTRACT

Except for protons, the chemical composition of solar cosmic rays is very similar to the abundance of the elements at the photosphere of the sun. If we consider the relative abundance ratio of protons to α-particles (P/α) at constant rigidity, this ratio is highly variable from one solar cosmic ray event to another. This ratio observed at the earth, however, decreases monotonically with time from the onset of solar flares and, furthermore, is dependent on the heliocentric distance of the parent flares from the central meridian of the solar disk. P/α's which have been measured before the onset of SC geomagnetic storms change from 1.5 to 50 or more, being a function of the westward position of the source from the east limb of the sun. These variations with respect to time and heliocentric distance suggest that the propagation of solar cosmic rays is strongly modulated in the interplanetary space. The major part of the α-particles seem to propagate as if they are trapped within the magnetic clouds which produce SC geomagnetic and cosmic ray storms at the earth.

The chemical composition and rigidity spectra of solar cosmic rays suggest that solar cosmic rays are mainly accelerated by the Fermi mechanism in solar flares. The observed variation of P/α's is produced mainly through the difference between the propagation characteristics of protons and α-particles.

1. Introduction

Recently, Freier and Webber (1963) have shown that, in the non-relativistic energy domain, the differential rigidity spectra of solar cosmic rays can be expressed by

$$\frac{dJ}{dP} = \left(\frac{dJ}{dP}\right)_o \exp\left(-P/P_c\right), \tag{1}$$

where P is the particle momentum per unit charge and the magnitude of P_o is equal for protons and α-particles. Thus the relative abundance ratio of solar protons to α-particles at constant rigidity is given by

$$\frac{\text{Number of protons (P)}}{\text{Number of }\alpha\text{-particles }(\alpha)} = \frac{(dJ/dP)_{o,P}}{(dJ/dP)_{o,\alpha}} \tag{2}$$

which is denoted by P/α in this paper.

The value of P/α is highly variable from one solar cosmic ray event to another. It has been suggested that the variability can be related to the type of solar cosmic ray events defined as F,F* and S types (Sakurai, 1965a). On the other hand, the relative abundance ratios of α-particles to medium and heavy nuclei at constant rigidity, which are defined by α/M and α/H, respectively, are nearly constant from event to event and are very similar to the relative abundance of elements observed at the photospheric surface of the sun (e.g., Biswas and Fichtel, 1964, 1965). These three ratios P/α, α/M and α/H seem to be useful for studying the acceleration and propagation mechanism of solar cosmic rays when we take into account the difference between the chemical abundances of solar cosmic rays and that of the sun.

In this paper, we will examine just the time variation and the heliocentric distance change of P/α by using the observational data available for this study. The acceleration and propagation mechanisms of solar cosmic rays will be considered based on the observed variation of P/α with respect to time as measured from the onset of solar flares and heliocentric distance as measured from the central meridian of the solar disk.

2. Observational Results and Their Implication

The observational data on P/α available for this study are summarized in Table 1. By using them, we obtain the variation of P/α with respect to the time interval from the onset of solar flares to the observation and the dependence of P/α on the heliocentric distance of the position of solar flares from the central meridian of the sun. These results are shown in Figs. 1 and 2, respectively. Fig. 1 shows that, with increasing time, the observed ratio P/α decreases momotonically and that, after the onset of SC geomagnetic storms, P/α is usually equal to about 1.

The value of P/α is very large especially for the component of solar cosmic rays which arrived promptly at the earth during the several hours after the onset of solar flares. In general, P/α for F-type and the earlier incident component of F*-type solar cosmic ray events is always much greater than 1 (Table 1). It thus seems that the particles which reach the earth's orbit mainly consist of protons. The P/α ratio for F-type events sometimes attains values of 50 or more and so seems to be different from and greater than the chemical abundance in the photosphere and the corona of the sun which has been estimated to be 6 or 7 by spectroscopic methods (e.g., Aller, 1961, 1965; Goldberg, Müller and Aller, 1960, Müller, 1966; Pottasch, 1964, 1966; Unsöld, 1969).

As is shown in Fig. 2, the large values of P/α are concentrated in the western-hemisphere of the sun and, except for the event on 3 September 1960, the value of P/α becomes greater with positions westward on the solar disk from the east limb with respect to the incident component of solar cosmic rays before the onset of SC geomagnetic storms. As is well known, most solar cosmic ray events of the F and F* types are generated from the parent solar flares located in the western hemisphere and the transit times of the initial incident component of solar cosmic rays from the sun to the earth usually become shorter as the position of the parent flares moves westward on the solar disk (Obayashi, 1964; Sakurai, 1965b). The results as shown in Figs. 1 and 2 indicate that the magnitude of P/α is determined by the position of the parent solar flares and by the type of solar cosmic ray events.

The SC maximum components of F*-type events are associated with the onset of SC geomagnetic storms. These components, therefore, seem to propagate in the interplanetary space while being trapped within solar magnetic clouds. This propagation process seems to be applicable to the SC maximum components associated with the solar cosmic ray events of S-type.

3. Acceleration and Propagation Mechanism of Solar Cosmic Rays

The relative abundance ratios of α-particles to medium and heavy nuclei, defined as α/M and α/H, have always been known to be nearly constant for every solar cosmic ray event and about equal to those at the photospheric surface of the sun (Biswas and Fichtel, 1965; Biswas, Fichtel and Guss, 1962, 1966; Biswas, Fichtel, Guss and Waddington, 1963; Durgaprasad, Fichtel, Guss and Reames, 1968). This constancy indicates that α/M and α/H do not vary with time as in the case of P/α. Consequently, the rigidity after acceleration and the manner of the propagation seem to be the same for α-particles, medium and heavy nuclei. As shown by Webber (1964) the propagation process does not affect the rigidity spectra of solar cosmic rays and so the initial spectra generated at flare sites is always the same as those observed at the earth. This fact would be useful when we consider the acceleration mechanism of solar cosmic rays.

The general theory of solar cosmic ray acceleration shows that, in the non-relativisitic energy domain, the acceleration rate for the Fermi mechanism is proportional to A/Z where A and Z are the mass and atomic numbers. Furthermore, this mechanism has proved to be successful in the interpretation of both the constancy of α/M and α/H and the exponential rigidity spectra of solar cosmic rays (e.g., Sakurai, 1965c, 1965d; Hayakawa et al., 1964). If the final rigidity of a nuclear particle, defined as R_f, is much greater than the initial one after acceleration, we do not need to consider the initial condition for acceleration. Thus R_f is given as follows (Sakurai, 1965d):

$$R_f = \frac{P_f c}{Ze} \simeq \eta \frac{A}{Z} \frac{M_o c^2}{e} \tau_Z, \qquad (3)$$

where P_f, c, e, M_o and η are the final momentum of the accelerated particle, the speed of light, the electronic charge, the rest mass of a proton, and the acceleration coefficient of the Fermi mechanism, respectively. Here, τ_Z is the time necessary for the particle to be acclerated to the rigidity R_f. From eq. (3), we obtain the relation

$$R_f = \frac{A}{Z} \frac{Mc}{e} \upsilon, \qquad (3)$$

where $P_f = AM\upsilon$ and M and υ are the mass of a proton and the speed of the particle, respectively. $M \cong M_o$ in the non-relativistic energy range. Since $A/Z \simeq 2$ in the cases of α-particles, medium and heavy nuclei, we can conclude that R_f is proportional to the speed υ and that τ_Z is the same for all these particles if the final rigidity is the same for them as discussed previously.

The final rigidity may be defined as the rigidity by which the accelerated particles can escape from the accelerating region. These particles are no longer accelerated and then ejected into the interplanetary space. As discussed before, the acceleration time τ_Z is the same for α-particles, medium and heavy nuclei to reach the same final rigidity. Consequently, the velocities for all nuclear species except for protons are about equal to each other. Based on the diffusion mechanism of solar cosmic rays in the interplanetary space as studied by Bryant et al. (1962), we can interpret the constancy of γ/M and α/H, as being independent of time since the propagation mechanism is the same for nuclear species except for protons.

As has been shown by Freier and Webber (1963), solar cosmic ray protons also have an exponential rigidity spectrum. This spectral form suggests that the Fermi mechanism is most effective for the acceleration in flare sites as in the case of heavier nuclei (Sakurai, 1965a, 1965c). Since $A/Z = 1$ in this case, the acceleration rate is two times lower than that for heavier nuclei according to eq. (3). Thus the time (τ_p) necessary for protons to attain the same final rigidity as that for α-particles is two times longer than that for α-particles (τ_α): $\tau_p = 2\tau_\alpha$.

The time necessary for solar cosmic rays to be accelerated has been estimated to be at most 2 to 3 minutes of the explosive phase of solar flares (e.g., Ellison, McKenna and Reid, 1961). A fraction of the protons and heavier nuclei can be accelerated to cosmic ray energy during this short time and then escape from the flare regions when they obtain the final rigidity of eq. (3).

If we assume τ_p to be $\sim 10^2$ seconds, τ_α is $\sim$ 50 seconds. This time is also applicable for medium and heavy nuclei. It is clear that these time intervals hardly affect the consideration of the propagation mechanism of solar cosmic rays since they are much shorter than the time necessary for the initial incident component of cosmic ray particles to traverse the path from the sun to the earth which ranges from about 30 minutes to 10 hours, being strongly dependent on the positions of the parent flares and the physical state of the interplanetary space. For that reason, we do not need to consider those short time intervals when we examine the propagation mechanism of solar cosmic rays.

It seems to be difficult to exaplin values of P/α as great as 50 for F-type events based only on the acceleration mechanism, although this fact suggests that the efficiency of proton acceleration is higher than that for the acceleration of heavier nuclei. As long as we refer only to the Fermi mechanism, we cannot, however, expect the acceleration rate for protons to be higher than that for α-particles. Furthermore, we cannot introduce such a high acceleration rate specified for protons even if we take into account the acceleration related to static electric fields or fluctuating electric fields produced by plasma oscillations (Sakurai, 1966). It is thus difficult to explain the time variation and heliocentric distance dependence of P/α as shown in Figs. 1 and 2 by taking only the acceleration mechanism into consideration.

The dependence of P/α on the heliocentric distance as shown in Fig. 2 seems to be explicable by considering the propagation mechanism related to the configuration of the interplanetary magnetic fields. The final rigidity of accelerated particles (eq. (3)) gives the relation

$$\upsilon_p \cong 2\upsilon_\alpha \quad (\upsilon_\alpha \simeq \upsilon_M \simeq \upsilon_H), \tag{4}$$

where υ_p, υ_α, υ_M and υ_H define the velocities of protons, α-particles, medium and heavy nuclei, respectively. Thus the diffusion time of protons from the sun to the earth (T_p) is about half to that of α-particles ($T\alpha$): $T_p \simeq (1/2)T\alpha$ and $T_\alpha \simeq T_M \simeq T_H$. As discussed before, we do not need to consider the times τ_p and τ_α in dealing with the diffusion of solar cosmic rays since they can be neglected as compared to the times T_p and $T\alpha$.

The solution of the simple diffusion equation thus gives the variation of P/α as a function of time which can be expressed as follows:

$$\frac{P}{\alpha} = \frac{1}{2\sqrt{2}} \left(\frac{P}{\alpha}\right)_o \exp\left(\frac{3T_\alpha}{4\tau}\right) \tag{5}$$

where $(P/\alpha)_o$ is the ratio at the flare regions and τ is the time. It is clear from this equation that the value of P/α reachs $\geqslant 50$ at $t \simeq 0.2\ T\alpha$ (= $0.1\ T_p$) or less when $(P/\alpha)_o = 6$. This suggests that the initial incident component of solar cosmic rays mainly consists of protons. With time greater than $T\alpha$ ($t \gg T\alpha$), eq. (5) is reduced to $(P/\alpha)_{t=\infty} \simeq \frac{1}{2\sqrt{2}}(P/\alpha)_o$. If we assume $(P/\alpha)_o$ to be 6 and 7 (Aller, 1961, 1965; Unsöld, 1969), we obtain $(P/\alpha)_{t=\infty}$ equal to 2.13 and 2.5, respectively. These values for $t \gg T\alpha$ are about twice as great as the observed value 1 ± 0.5 as is shown in Fig. 1. This result suggests that the propagation mechanism of α-particles is different from that of protons.

Since $v_{\alpha} \simeq v_M \simeq v_H$, the simple diffusion theory also gives the time-independent ratios on α/M and α/H which are the same as those at the sun. This is an interpretation of the constancy of α/M and α/H. The diffusion coefficient for α-patticles, medium and heavy nuclei seems to be smaller than that for protons.

The relation of P/α with the types of solar cosmic ray events as considered previously (Sakurai, 1965a) cannot be explained by taking only the simple diffusion theory into consideration. In view of the fact that α-particles are much more abundant for the SC maximum component of F* and S type events, the major part of α-particles seem to propagate through the interplanetary space as if they are trapped within the magnetic clouds which produce SC geomagnetic and cosmic ray storms at the earth. This seems to be a reason why the value of P/α is 1 ± 0.5

For the 3 September 1960 event, the earliest incident component of solar cosmic rays took about 7.5 hours to arrive at the earth's orbit since the particles had to diffuse across the interplanetary magnetic fields from the flare region located at the east limb. The value of P/α for this event is contrary to the general dependence of P/α on the heliographic longitude as shown in Fig. 2. This event suggests that, when propagating across the interplanetary magnetic fields, the diffusion coefficient for α-particles is much smaller than that which is applicable to the simple diffusion theory.

4. Concluding Remarks

The acceleration and propagation mechanisms of solar cosmic rays have been discussed based on the time variation (Fig. 1) and the heliocentric distance dependence (Fig. 2) of P/α, the exponential rigidity spectra and the constancy of α/M and α/H. In order to reach a clear-cut conclusion on these mechanisms, however, we need much more observational data on P/α. At present, we do not have the spectroscopic method for determining the relative abundance of helium at the sun, but, in the near future, we may solve this problem if we can obtain sufficient observational data on P/α and its time change and heliographic dependence. The solution of this problem will provide important information on the origin of the chemical abundance in cosmic space and the evolution of the sun. The acceleration mechanism of solar cosmic rays in solar flares is very important for the investigation of the origin of cosmic rays in the Galaxy because the sun is the only star for which we can directly observe the acceleration and ejection of high-energy particles of cosmic ray energy in surface disturbances. It is especially important to obtain some information on the injection process of solar cosmic rays.

It has proved to be difficult to interpret the time variation of P/α by taking only the simple diffusion theory into account. The diffusion coefficient of α-particles, medium and heavy nuclei across the interplanetary magnetic fields seems to be smaller than that parallel to these fields. The diffusion between the propagation mechanisms of protons and α-particles would give an important clue as to the fine structure of the interplanetary magnetic field configuration.

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TABLE 1. RELATIVE ABUNDANCE RATIO OF PROTONS TO HELIUM NUCLEI (P/α) AND RELATED PHENOMENA

Solar Flare Date	Time		Position		Imp.	Measured Time*	P/α	Type of PCA	Remark	Literature**
1958 March 23	09	50	S14	E77	3+	○	1.0 ± 0.5	S		1
July 29	03	03	S14	W43	3	●	≥ 10	F	No SC storm	3
Aug 22	14	17	N18	W09	3	●	7.5 ± 1	F*		3
1959 May 10	20	55	N23	E47	3+	○	1.0 ± 0.5	F*	SC Max. Comp.	1
July 10	02	10	N22	E66	3+	● ○	1.4 ± 0.3 5.0 ± 1.0	F*		1,2
July 14	03	42	N16	E07	3+	○	1.0 ± 0.5	F*		1
July 16	21	15	N08	W32	3+	○	1.0 ± 0.5	F*	SC Max. Comp.	1
1960 May 4	10	15	N12	W90	3	●	≥ 50	F	No SC storm	1,2
Sept. 3	00	37	N20	E88	3	● ○	40 30	F*		1,2
Nov. 12	13	23	N27	W04	3+	● ○	5.5 ± 0.5 1.0 ± 0.5	F*	SC Max. Comp.	2
1961 July 18	09	21	S06	W58	3+	●	6 ± 1	F*		1,2
1966 Sept 2	05	48	N23	W55	3B	●	16 ± 2	F		4

* Black circle: Measurement before the onset of SC storm
Open circle: Measurement after the onset of SC storm

** 1) Freier and Webber (1963), 2) Biswas and Frichtel (1965), 3) Hakura (1967) and private communication and 4) Durgaprasad, Frichtel, Guss and Reames (1968).

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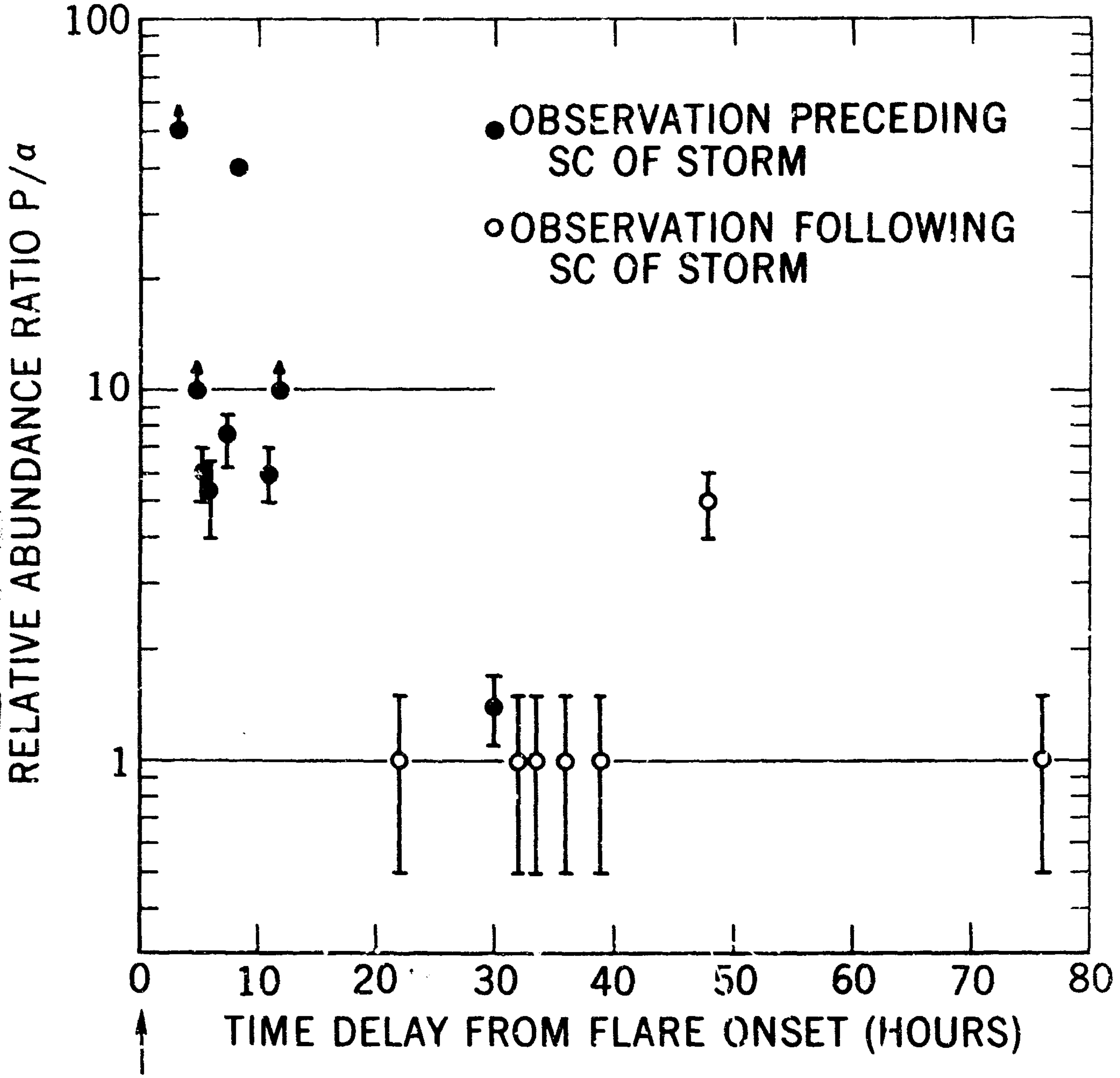

Figure 1. - Time variation of P/α in solar cosmic rays. The observed values of P/α before the onset of SC geomagnetic storms are indicated by the black circles, and those after the storm onset by the open circles.

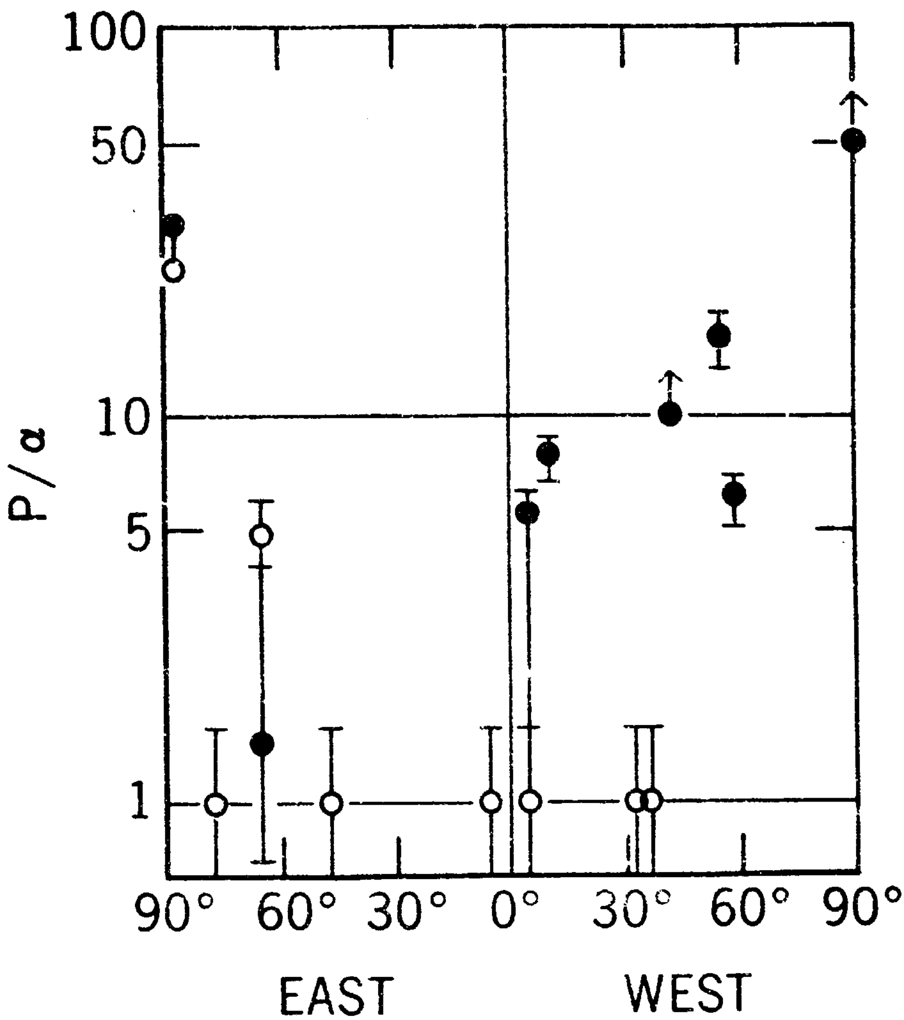

Figure 2. - Variation of P/α with respect to the angular distance from the central meridian of the solar disk. The black and open circles indicate the observed values of P/α before and after the onset of SC geomagnetic storms, respectively.