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ABSTRACT

Solar proton flares take place due to the release of magnetic energy accumulated within the sunspot magnetic flux tube of force lying in the chromosphere and the lower corona due to the twisting of it, which is seen from the rotational motion of sunspot groups on the photospheric surface. This rotational motion is counterclockwise (clockwise) in the northern (southern) hemisphere when viewed from the earth. The accumulation of magnetic energy within the flux tube due to this motion continues to proceed until some instability is induced along the flux tube. It is further shown that the magnetic configuration of sunspot groups is important for the triggering of a solar proton flare.

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1. Introduction

Most solar proton flares which have been observed so far took place within the sunspot groups classified as β and $\beta\gamma$ types (Ellison, McKenna and Reid, 1961; Noyes, 1962; Malitson, 1963). Warwick (1966) has further shown that these sunspot groups can also be classified as the δ-type, which has been proposed by Künzel (1960). According to Bray and Loughead (1962), the sunspot groups classified as δ-type are generally born in the one large umbra, within which magnetic fields with both north and south polarities exist together.

Sakurai (1967) has recently found the existence of rotational motion of sunspot groups, within which solar proton flares often took place, during the passage over the solar disk. When viewed from the earth, this rotational motion is counterclockwise in the northern hemisphere and vice versa. Under the influence of this rotational motion, the magnetic lines of force extending from the sunspot region over the photosphere seem to be strongly twisted in the chromosphere and the lower corona.

The twisting motion of magnetic lines of force accumulates some amount of magnetic energy within sunspot magnetic flux tubes. As this motion proceeds, therefore, the accumulation of such magnetic energy goes on. When that magnetic energy accumulated above the sunspot group is released by some triggering action, a solar flare will take place, although the mechanism of release or the triggering process of such an instability is still unknown.

Since, fortunately there are extensive data on sunspot magnetic fields and related phenomena during the IGY (Ellison, 1962), we can examine some relation of the rotating motion of sunspot groups with the occurrence of solar proton flares. This relation will be considered here with the purpose of making clear both the mechanism of proton flares and the acceleration mechanism of energetic particles. Further, the triggering mechanism of proton flares will be briefly discussed.

2. The Magnetic Structure of Solar Proton Flare Regions

Many solar proton events have been observed during the IGY (July 1957 - December 1958) and compiled by many authors in form of Tables (for example, Obayashi, 1962; Maeda et al., 1962; McDonald, 1963; Fritzová and Švestka, 1966, Obayashi et al., 1967). In this paper, the data on solar proton flares compiled by Obayashi et al., (1967) is used to analyze the relation of proton flares with the magnetic structure of sunspot groups. The extensive data on sunspot magnetic fields edited by Ellison (1962) are also used.

The data on solar proton flares and related sunspot groups are summarized in Table 1, using both the data mentioned above. In this Table, the distribution of the magnetic polarities of sunspot groups is also indicated which shows the evidence for the rotating motion of sunspot groups. The remark "yes" in the last column of the Table indicates that solar proton flares took place within the sunspot groups within which the magnetic fields were peculiarly distributed as to polarity as shown in Figs. 1 and 2. The distribution of magnetic fields shown in these figures is somewhat different from the well-known distribution of magnetic polarity within sunspot group during the current solar cycle (for example, Kiepenheuer, 1953). As is evident from Figs. 1 and 2, the magnetic region for the preceding part of sunspot groups is located somewhat northward of that for the following one. In the southern hemisphere, the situation is reversed. This feature is significantly different from that of the most sunspot groups which did not produce solar proton flares.

This peculiar distribution of magnetic polarity within sunspot groups appears to reflect upon the rotational motion of sunspot group. As has been shown by Sakurai (1967), such rotational motion is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere, when viewed from the earth. The progression of this rotational motion is quite clear when one refers to the cases for the two sunspot groups which appeared in September 1963 (Elliott and Reid, 1965) and in July 1961 (Bruzek, 1964). These two sunspot groups showed the well-defined rotational motions, counterclockwise and clockwise, respectively, since the former and the latter appeared in the northern and southern hemispheres. Such rotational motion seems to produce the twisting of sunspot magnetic lines of force in the chromosphere and the lower corona.

As a result of this rotational motion, the magnetic field distribution of sunspot group is occasionally reversed as seen in the case on July 7, 1958. When the life time of sunspot groups is from three to four months as in the case from March to May, 1960, the magnetic field distribution of sunspot groups becomes quite peculiar and shows the reverse sense of polarity distribution in comparison with that for the current solar cycle (for example, Ellison, McKenna and Reid, 1960; Waldmeier, 1960). This sunspot group has produced solar cosmic rays many times during its lifetime, as indicated by

Obayashi et al., (1967) and Sakurai (1967).

Major solar proton events took place twenty-one times during the IGY as summarized in Table 1, among which eighteen events (or about 80 percent of listed events) were associated with the sunspot groups which had the peculiar structure of magnetic field distribution considered earlier in this paper. Consequently, one can conclude that the occurrence of most solar proton flares is closely related to the growth of the twisting of sunspot magnetic fields, which is produced by the rotational motion and that this twisting plays an important role in triggering the onset of a solar flare.

As has been shown by Anderson (1961), the sunspot groups which produce solar proton flares are always surrounded by the one big penumbra. It thus follows that both polarity regions of sunspots are involved within the same penumbra.

As was shown above, the occurrence of solar proton flares is clearly connected with the twisting of sunspot magnetic field lines due to the rotational motion of sunspot groups, which might be driven by the convective motion near the photospheric surface through the coupling of the differential rotational flow and the effect of the Coriolis force in the solar atmosphere such as has been considered by Parker (1955) and Babcock (1961).

3. Triggering of Solar Proton Flares and the Acceleration of Energetic Particles.

The cause of solar proton flares seems to be closely associated with the twisting motion of parent sunspot groups as discussed earlier (Sakurai, 1967). The twisting motion of magnetic lines of force gradually accumulates magnetic energy within the magnetic flux tube.

As has been discussed by Parker (1957) and Sweet (1958a), the magnetic configuration of sunspot groups is of the force-free type whenever the sunspot magnetic fields are stable, and so the magnetic lines of force extending into the solar atmosphere over the sunspot groups are necessarily twisted (Gold and Hoyle, 1960; Longmire, 1963; Sakurai, 1967).

While accumulating magnetic energy within the magnetic flux tube through the twisting of magnetic lines of force, the magnetic configuration of sunspot groups gradually approach an unstable state such as has been discussed by Alfvén (1950), Lundquist (1950) and Longmire (1963). When the inequality $(\nabla \times B) \times B \neq 0$ is once attained when viewed from the photosphere, where B is magnetic field, the configuration of sunspot magnetic fields becomes unstable (Sakurai, 1967). As a result, the magnetic flux tube obtains a strong buoyant force and then tends to move upward. Consequently, the twisting of magnetic flux tube is strongly enhanced and many kinks are formed along the magnetic flux tube. Then, most of the accumulated magnetic energy is released at once to the trapped particles and surrounding ambient plasma through the severing and reconnection of magnetic lines of force.

Since the twisting of magnetic flux tube often produces several kinks along the flux tube as the twisting goes on, the unstable condition is at first produced in or near the areas of kink formation (Lundquist, 1950). The magnetic structure in or near the areas where such kinks are formed is, though complicated, very similar to the X-type neutral layers which have been discussed by many authors (for example, Sweet, 1958a, b; 1964; Dungey, 1958; 1959; Parker, 1957, 1963; Petschek, 1964; Petschek and Thorne, 1968; Green and Sweet, 1968). Since the progression of twisting of a magnetic flux tube forms many kinks along the flux tube, as considered by Alfvén (1950), some instability will develop at each of such kinks along the flux tube and necessarily generate turbulent-like magnetic irregularities within the flux tube (Wentzel, 1964). Thus, a solar proton flare suddenly develops.

The development of such instability just mentioned is necessarily accompanied by the chaotic motion of magnetic lines of force due to severing and reconnecting action of them. As a result, thermal particles trapped by these magnetic lines of force will be accelerated through the interaction with those moving magnetic lines of force. Energetic particles such as solar cosmic ray protons, heavier nuclei and energetic electrons responsible for the emission of type IV radio bursts will thus be generated.

Once the inequality $(\nabla \times \vec{B}) \times \vec{B} \neq 0$ is attained, the magnetic flux tube over sunspot groups will be strongly pushed upward as has been mentioned before. This magnetic flux tube will be severed by a similar mechanism as discussed by Kawabata (1966) and become magnetic clouds which pass away into the interplanetary space through the solar corona. These clouds may be identified with the plasma clouds producing geomagnetic and cosmic-ray storms.

Solar cosmic ray protons and heavier nuclei and energetic electrons seems to be accelerated due mainly to the Fermi mechanism as has been shown by the use of the data on the rigidity spectra and the chemical composition of solar cosmic rays (Wentzel, 1965;

Sakurai, 1965 a, b), because the magnetic lines of force lying within the flare regions are violently disturbed in space and time.

4. Discussion

Most solar proton flares take place within sunspot groups where the distribution of magnetic fields is peculiar compared to that of most sunspot groups currently observed. Those sunspot groups appear to be driven to rotate during their lives on the solar disk by some force, the origin of which may be related to the birth and growth of sunspot groups. Although the origin of this force has not yet been made clear, it seems that the rotational motion of sunspot groups gradually leads to the twisting of sunspot magnetic field lines extending into the chromosphere and the lower corona, and consequently accumulates some amount of magnetic energy within the magnetic flux tube.

As has been discussed by Anderson (1961), the developing stage of sunspot groups is important to the triggering processes of solar proton flares, because most flares take place within the sunspot groups of type E and F. At these stages, sunspot groups are almost always surrounded by one large penumbra (Anderson, 1961; Ellison, 1962), and can therefore be classified as δ-type (Warwick, 1966).

Consequently, it should be possible to forcast the occurrence of solar proton flares by examining observationally the magnetic and optical structure of well developed sunspot groups on the solar disk. Since the prediction of solar proton flares based on the radio observation of solar active region (Tanaka and Kakinuma, 1964), has sometimes been successful, the radio observations on the solar active regions will be useful along with the detailed observation on the magnetic structure of these regions.

5. Concluding Remarks

It has been found that the twisting of sunspot magnetic lines of force over sunspot groups due to their rotational motion near the photosphere is important to the occurrence of solar proton flares, although the causal relation of this twisting with the triggering process of solar flares is still unknown. Consequently, this relation must be studied from a plasma dynamical point of view.

The characteristic time of the growth of solar proton flares as deduced from various current theories (for example, Parker, 1963) is always too long to explain the observed time scales of solar proton flares. This may imply that the triggering of proton flares takes place at many points along the unstable twisted magnetic flux tube which shows the filamentary structure (Sakurai, 1968).

It has been shown in this paper by the use of the observational data on the distribution of magnetic fields over the sunspot groups that the magnetic configuration of sunspot groups is most important for the occurrence of solar proton flares.

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CAPTION OF FIGURES

Fig. 1. Magnetic field distribution of sunspot group which produced the solar proton flare on July 7, 1958 (Sunspot group number 13356) (Ellison, 1962). This is an example in the northern hemisphere.

Fig. 2. Magnetic field distribution of sunspot group which produced the solar proton flare on October 20, 1957 (Sunspot group number 12689). This is an example in the southern hemisphere.

TABLE 1

LIST OF MAJOR SOLAR PROTON FLARES AND RELATED SUNSPOT GROUPS DURING THE IGY

Month		Date	Solar Start (UT)	Flare Position		Imp	PCA Imp*	Sunspot Group No	Type**	Remarks
1957	July	03	0719	N12	W41	3	3	12434	Yes	
	Aug.	09	0622	N09	E76	2	2	12540	Yes	
		28	0810	S30	E32	3+	3	12579	Yes	
		31	1300	N25	W01	3	3	12580	Yes	
	Sept.	02	1257	S34	W36	2	3	12589	No	
		03	1424	N24	W29	3	2	12580	Yes	white light flare
		11	0245	N17	E05	3	2	12596	Yes	
		21	1332	N10	W07	2	2	12634	No	
		22	0558	N10	W14	2	3	12634	Yes	
	Oct.	20	1637	S28	W38	3+	2	12689	Yes	
1958	Feb.	09	2108	S11	W15	2	3	13000	Yes	
	March	14	1454	S21	W85	2	3	13067	No	
		23	0955	S14	E78	3+	3+	13103	No	white light flare
	June	04	2147	N27	W59	2	1	13275	Yes	
	July	07	0023	N26	W05	3+	3±	13356	Yes	very peculiar
		29	0259	S14	W44	3	2	13388	Yes	
	Aug.	16	0432	S14	W51	3+	3	13434	Yes	
		20	0042	N15	E17	3	2	13464	Yes	
		22	1422	N18	W10	3	3	13464	Yes	
		26	0005	N20	W54	3+	3+	13464	No	Decaying sunspot
	Sept.	22	1012	N17	W65	2	3	13535	Yes	

*The importance of polar cap absorption (PCA) is given as follows (Obayashi et al., 1967): using f-min at Resolute Bay,

Importance 1	Increase of f-min $>$ 3 Mc/s and the duration $<$ 6 hours
Importance 2	Increase of f-min $\geq$ 5 Mc/s or the duration of black out $>$ 6 hours.
Importance 3	Duration of black out $>$ 24 hours.
Importance 3+	Duration of black out $>$ 48 hours.

** See text about the meaning of type

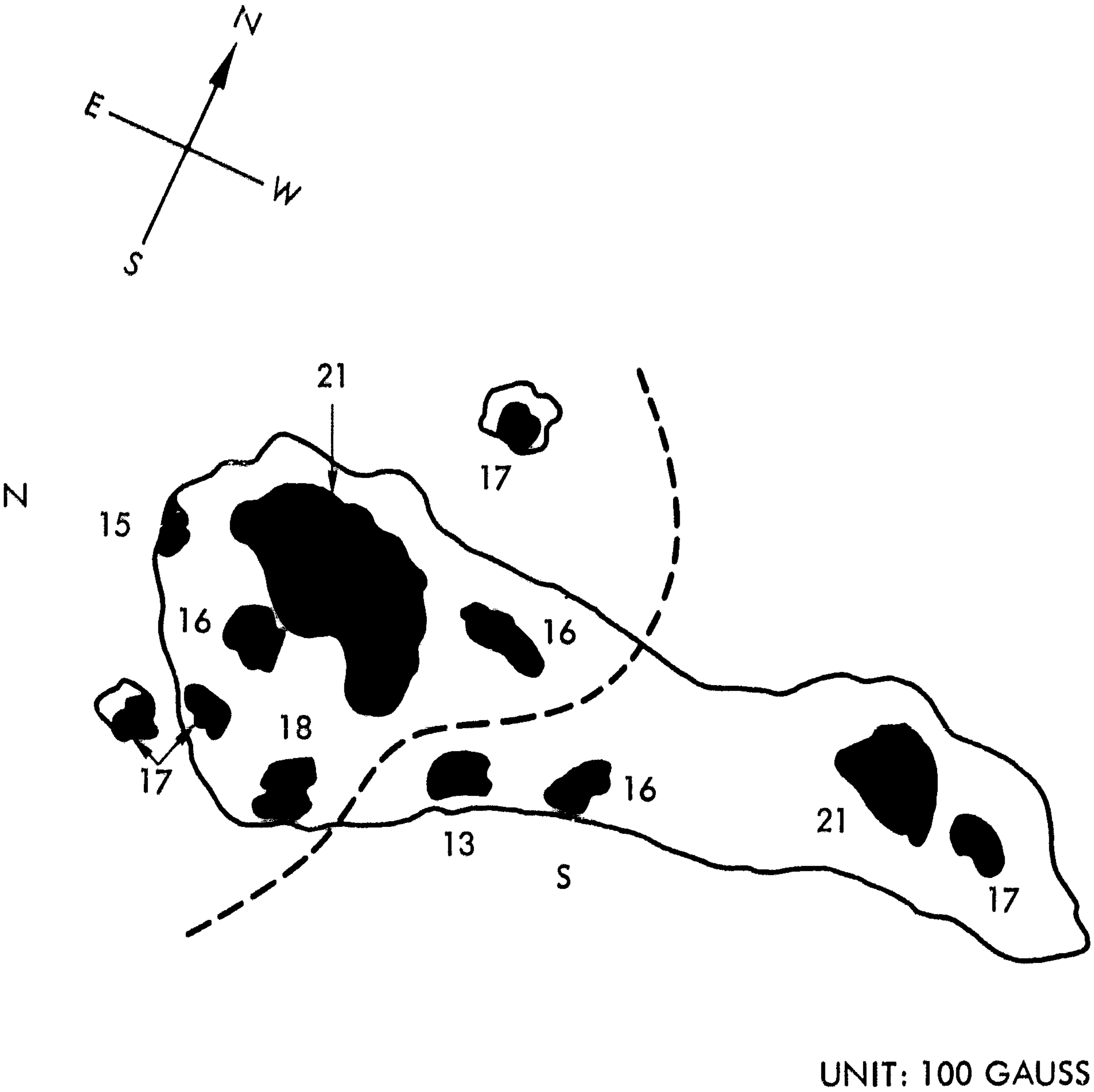

Figure 1.

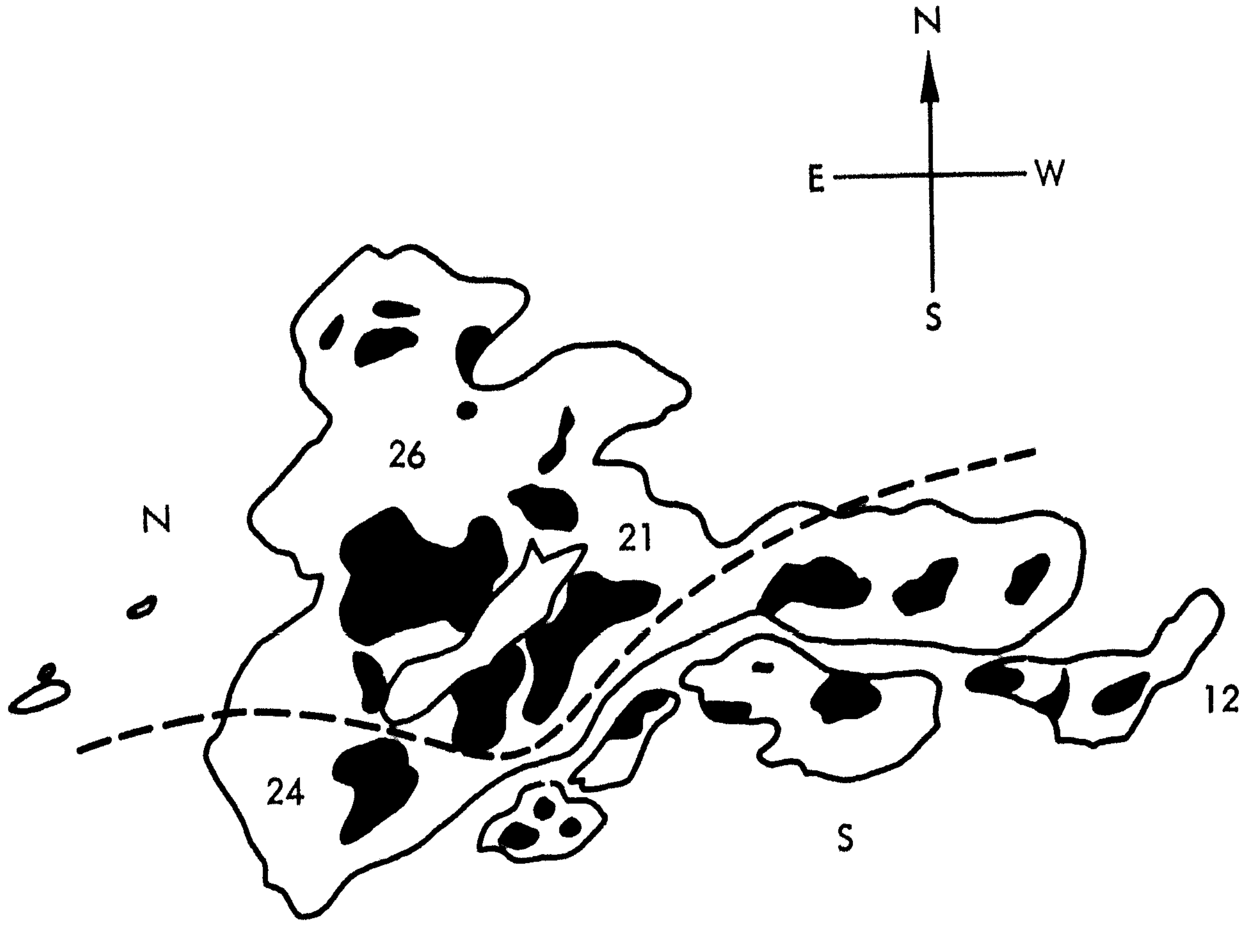

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Figure 2.