

Solar Flare Emissions & Geophysical Disturbances

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Various geophysical phenomena are produced by both wave and particle emission from solar flares. In understanding these phenomena, it is necessary to investigate the nature of these emissions and solar flare phenomena. Using the observed data for these emissions, a review is given on the nature of solar flares and their development. Geophysical phenomena are discussed by referring to the results for solar flare phenomena.

1. Introduction

SUDDEN IONOSPHERIC disturbances (SIDs) are always associated with solar flares, which emit X-rays¹⁻³ of wavelength shorter than about 5 Å. These X-rays ionize the atmospheric constituents of the lower region of the ionosphere, in particular, the D and E regions. At present, it is known that various wave and particle emissions are associated with solar flares: hard and soft X-ray bursts, EUV emissions, radio bursts of spectral types II, III, IV and V, microwave-impulsive bursts, solar cosmic ray protons, heavier nuclei and electrons, corpuscular clouds and shock waves⁴.

Although every flare is not accompanied by all of these emissions just mentioned, a major flare of importance 4B (or 3+) generally produces all of these emissions. It is now known that solar cosmic rays of MeV energy and corpuscular clouds are the sources for the polar cap absorption and geomagnetic storms, respectively. Shock waves associated with flares tend to propagate outward from the flare region and seem to reach sometimes near the earth's orbit or beyond. When they encounter the earth, sudden storm commencements (SSCs) are often observed at the earth. These SSCs are also observed by satellites as the jump of magnetic field intensity, plasma flow speeds and other factors^{5,6}.

Those geophysical phenomena are all of solar flare origin^{7,8}. Thus it seems very important to investigate the development of solar flares and their associated phenomena. At present, solar flares are usually observed by the hydrogen Balmer alpha line (H_{α} , $\lambda=6563\text{\AA}$), which gives us an important information for the structure of flares in the chromospheric regions

of the sun^{9,10}. In addition to this line, several other lines like H_{β} , Ca-II H and K are used in accordance with different purposes for the flare investigation. At present, we have methods to observe flares by using various wave emissions other than these spectral lines. For instance, solar X-ray and radio emissions associated with flares give many important informations on the development of flares and its relation to these emissions. These informations are also very important to study the mechanism of flares.

Though indirectly studied, SIDs are also useful to study the development and mechanism of flares, because we are able to find a clue to estimate the time profiles of X-ray and EUV emission intensities which give additional informations to direct observations by satellites and rockets. Since, at present, we do not know yet the mechanism of solar flares and its relation to the particle acceleration processes, it is still necessary to take every possibility for observations in order to understand solar flares and associated phenomena.

The study of geomagnetic and cosmic ray storms enables us to estimate the propagation pattern of interplanetary disturbances associated with flares. This problem is under study by taking into account the magnetic and plasma data obtained by satellites and deep spacecrafts¹¹.

In this paper, we shall first review the observational results on solar terrestrial relationships and then consider solar flare phenomena and their relation to geophysical events. By taking into account the development of flares and various associated emissions, flare-associated disturbances at the earth will be interpreted. Forecasting technique of flare occurrences will also be discussed briefly to give an insight to search for the cause of geophysical phenomena.

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2. Geophysical Disturbances Associated with Solar Flares

Solar flares, in general, produce both waves and particle emissions. Among these emissions, X-rays and EUV rays are responsible for SID phenomena, while MeV-particles emitted by flares produce the polar cap absorption. In association with flares, shock waves and corpuscular clouds are often generated in the flare regions. After ejection, these waves and clouds sometimes approach the earth's orbit and then generate SSCs and geomagnetic storms, respectively. In this section, we shall therefore, review these three emissions from the sun by referring to the results observed on the earth. Detailed descriptions for these results are useful to further study of solar-terrestrial relationships.

2.1 SIDs

SIDs are generated as a result of the sudden increase of the ionization density in the lower region of the ionosphere except for SFD (sudden frequency deviation) and the increase of the critical frequency f_oF2 . As shown in Fig. 1, for instance, various

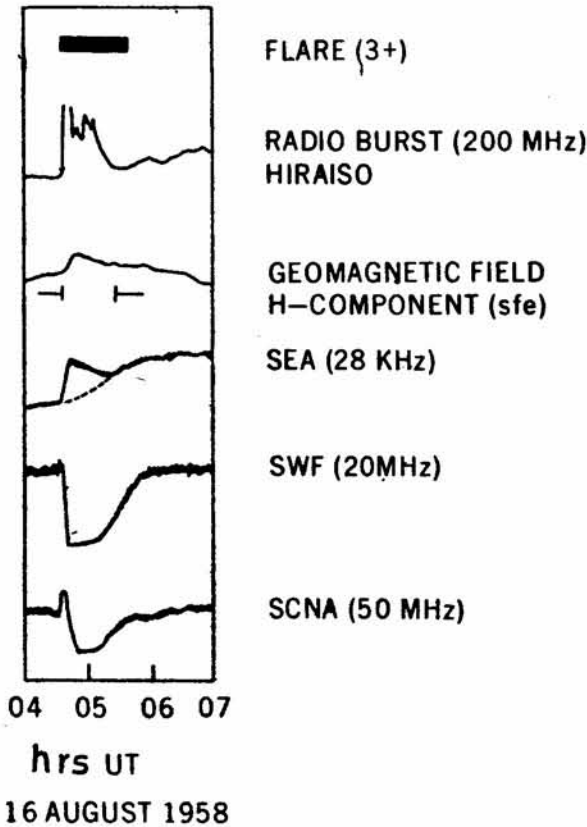


Fig. 1—An example of SID associated with the solar flare of 16 August 1958 (As a reference, the time profile of radio flux at 200 MHz is shown¹³)

SOLAR-TERRESTRIAL EVENTS ON AUGUST 16-18, 1958.

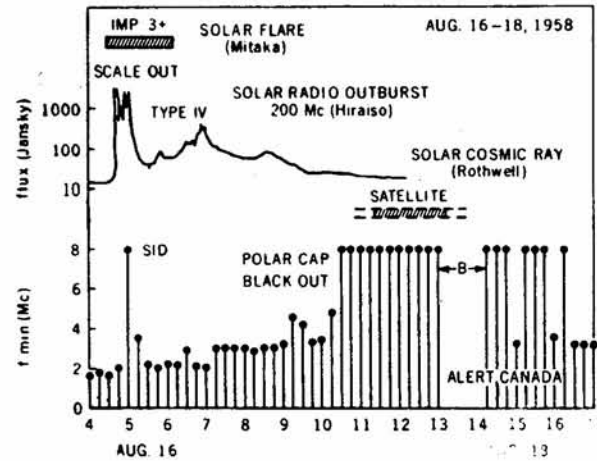


Fig. 2—Polar cap absorption produced by the invasion of solar cosmic rays as observed at Alert, Canada¹⁴

phenomena occurred in association with the flare of 16 August 1958^{12,13}. In this figure, SEA (Sudden enhancement of atmospheric), SWF (Short wave fade-out), SCNA (Sudden cosmic noise absorption) and sfe (Solar flare effect on geomagnetism) are described with the flare duration and the time-profile of type IV radio burst at 200 MHz. These phenomena associated with ionospheric disturbances are called SIDs.

In addition to the phenomena shown in Fig. 1, it is known that SFD, SPA (Sudden phase anomaly), f -min increase and the increase of f_oF2 are often associated with flares. SIDs such as SEA, SCNA, SWF, sfe and SPA are generated as a result of increased ionization of the lower regions of the ionosphere, i.e. the ionospheric D and E regions, whereas SFD and the f_oF2 increase are related to the increase of the ionization density in the lower portion of the ionospheric F2 region. This indicates that the cause of both SFD and the f_oF2 increase is different from those which produce other SID phenomena; that is, the cause is dependent on the depth of the penetration of solar emissions into the ionospheric regions. Therefore, the investigation of SIDs can give important clue to clarify the spectral distribution of flare-associated emissions responsible for ionizing the ionosphere.

2.2. Polar Cap Absorption

The solar flare of 16 August 1958 was also accompanied by the polar cap absorption (PCA), which was detected¹⁴ as the increase of f -min (see Fig. 2). Several hours after the onset of this flare, the ionosonde at Alert, Canada, recorded the increase of

f -min for about several hours. Almost simultaneously with this ground-based observation, the satellite, Explorer 2 just detected MeV solar particles¹⁵. These solar particles were emitted from the flare described in this figure, which occurred at 0432 hours UT of 16 August. This flare was associated with type II burst at metric frequencies and type IV radio burst of wide frequency band.

This PCA is produced by the enhanced ionization in the upper atmosphere (50-100 km high) over the polar cap regions due to the invasion of MeV solar cosmic ray particles^{14,16-19}. Because of this ionization the commercial and standard VLF radio waves of the polar routes is affected^{20,21} in a way similar to SEA and SPA as described in subsection 2.1. Phase variation of these waves is clearly observed just after the invasion of MeV solar cosmic ray particles starts.

During the IGY and IGC, several polar ionospheric observing stations were equipped with riometers to measure the cosmic noise absorption due to ionospheric disturbances. Later on, the riometers were shown to be useful to study solar cosmic ray events because the enhanced ionization by solar cosmic ray invasion produces SCNAs for the riometer absorption records^{17,22,24}. Leinbach²² extensively studied the patterns of the development of this absorption and made clear that the processes of solar cosmic ray invasion over the polar cap regions are classified²⁵ into several types: they are currently called F, F*, S and mixed types, as shown in Fig. 3.

The cause of these types of events is related to the difference of the propagation mechanism of these solar cosmic rays in interplanetary space. This problem has been extensively investigated by many workers^{22,26-30}. At present, it is known that the chemical composition of solar cosmic rays plays an important role on the formation of the developmental pattern of MeV solar cosmic ray events^{26,27,29}. Hakura²⁶ indicates that, in a typical event, there exists three stages for the development, each of which is closely related to the invasion of electrons, protons and helium nuclei over the polar cap regions. Therefore, the investigation of the developmental pattern of solar cosmic ray events gives us some important information for the acceleration and propagation mechanism of solar cosmic rays.

As is clearly seen in Fig. 3, S type events are associated with the development of SSC geomagnetic storms. This suggests that the particles for these events are transported by corpuscular clouds which produce these geomagnetic storms^{14,25,28,30,31}.

2.3. Geomagnetic Storms

A few days or more after the onset of solar flares,

geomagnetic storms are sometimes observed at the earth. These storms start with the sharp increase of the horizontal intensity of the geomagnetic field, which is defined as the SSC. A typical example is shown in Fig. 4. In this figure, the three components of the geomagnetic field are described; they are the horizontal (H) and vertical (Z) intensities and the declination (D). By analyzing these components and their time variation, we are able to investigate the development and structure of geomagnetic storms. As is seen in this figure, several hours after the SSC, the horizontal component starts to sharply decrease in its intensity. After it reached a minimum, this component is recovered within a week or two to the state before the onset of storms.

The Forbush decrease of cosmic rays, aurora and the auroral zone absorption (AZA) usually occur in association with geomagnetic storm. These phenomena are, therefore, triggered by some mechanism connected with the cause of geomagnetic storm³². This suggests that it is most important to know the mechanism of geomagnetic storm, because we can

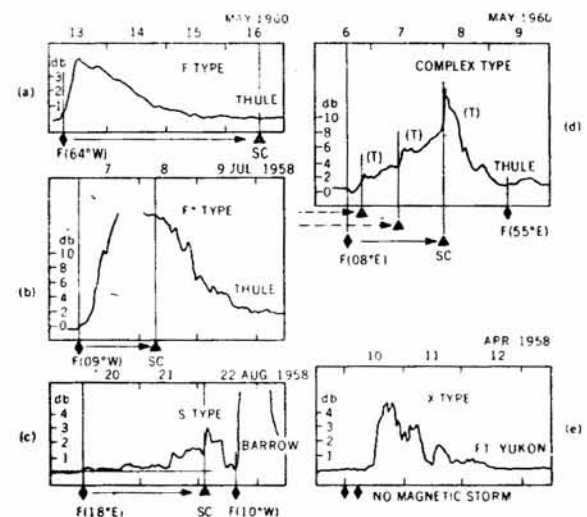


Fig. 3—Developmental patterns of polar cap absorption events as observed by the riometers (The times for solar flares and SSC are indicated)

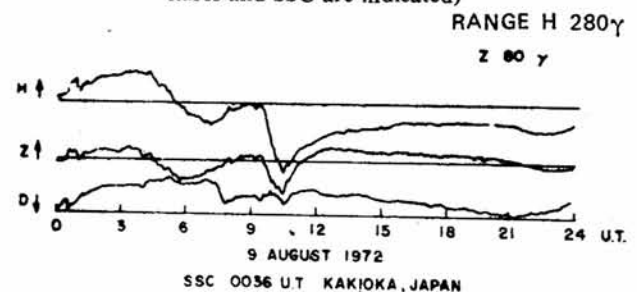


Fig. 4—An example of geomagnetic storm as recorded on the earth (Three components, viz. H , D and Z are indicated)

find out the physical relationships of this storm with the Forbush decrease, auroral and other phenomena once we can understand this mechanism. It is explained that SSC occurs as a result of the interaction of the geomagnetic field with interplanetary shock waves or disturbances generated by solar flares^{33,34}. In association with geomagnetic storm as shown in Fig. 4, substorms develop at first over the polar cap regions, and then extend to the lower latitude regions. The expansion of the auroral zone to lower latitudes is also seen during the main phase of storms.

At present, satellite observations show that interplanetary shock waves passing through the earth's magnetosphere are responsible for SSC of geomagnetic storms^{35,36}. These waves seem to have been sometimes produced as blast waves in solar flares. As shown by Chao *et al.*⁶, the shock waves producing type II radio bursts are not always able to reach the earth's orbit without heavy dissipation. Therefore, the shock waves observed at the earth's orbit by satellites may have originated somewhere between the sun and the earth by the action of flare-ejecta, while they are sweeping through interplanetary space after ejection by flares.

When we investigate the time differences between flares and associated SSCs as a function of the longitudinal position of these flares, we are able to find a statistical pattern of the propagation of interplanetary disturbances generated by flares^{37,38}. Fig. 5 indicates that these time differences are dependent on the position of parent flares and that the minimum is reached when flares occur about 30° west of the

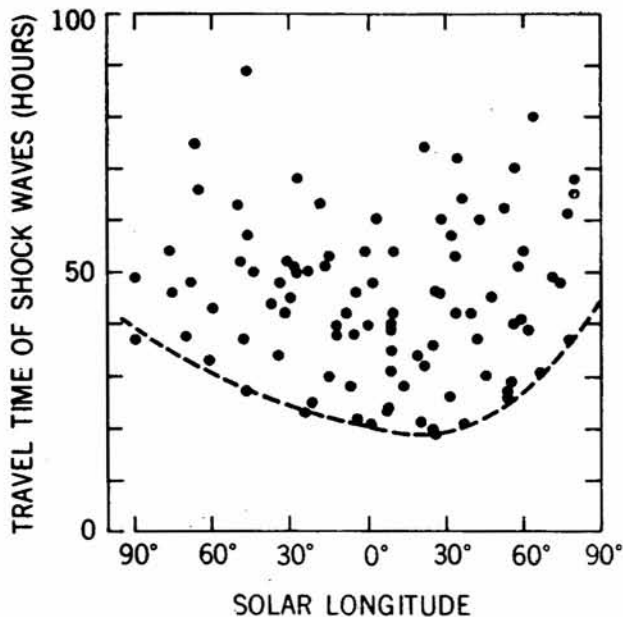


Fig. 5—Relation between flare positions on the sun and the time intervals from flares to SSC onsets

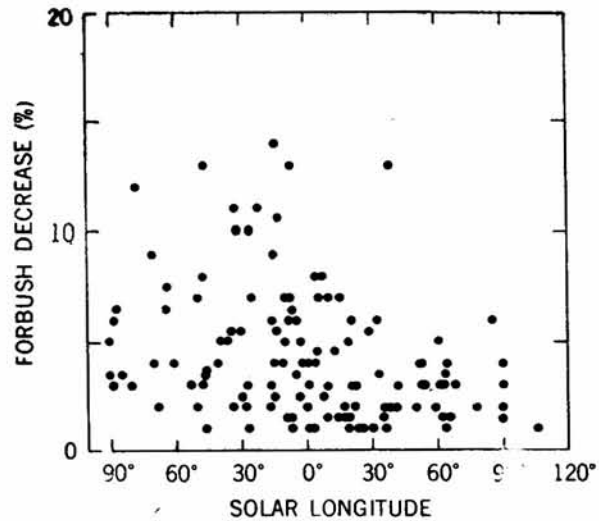


Fig. 6—Magnitudes of the Forbush decrease of galactic cosmic rays as a function of the longitudinal position of associated flares on the sun

central meridian of the solar disk. The average of these data shown in this figure, also shows that the minimum mean time difference is observed when a flare occurs 20-30° west of the central meridian plane of the solar disk³⁸. This result suggests that flare-generated interplanetary disturbances tend to propagate eastward from the flare region. This pattern of their propagation has recently been obtained by Ness and his colleagues^{35,39,40}; their results suggest that the formation of this pattern is closely related to the mechanism of their generation in the flare region, because it is known that the shock waves indirectly observed as the moving source of type II radio bursts tend to propagate along the magnetic fields near and above the flare region⁴¹⁻⁴³.

While propagating through interplanetary space, these disturbances may deform the configuration of the interplanetary magnetic field between the sun and the earth. This variation of the field seems to have been examined by analyzing the field strength and direction in the region behind the propagating front of these disturbances⁴⁴. Furthermore, this variation would affect the Forbush decrease of galactic cosmic rays during geomagnetic storms. Sinno⁴⁵ found that this decrease is highly dependent on the longitudinal position of parent flares on the solar disk. As shown in Fig. 6, the percentage of this decrease tends to increase as the flare position moves eastward over the solar disk^{28,46}. This result, furthermore, indicates that some flare-ejecta tend to change the configuration of the interplanetary magnetic field; in this case, the western portion of these ejecta must produce high field intensity region just behind the propagating

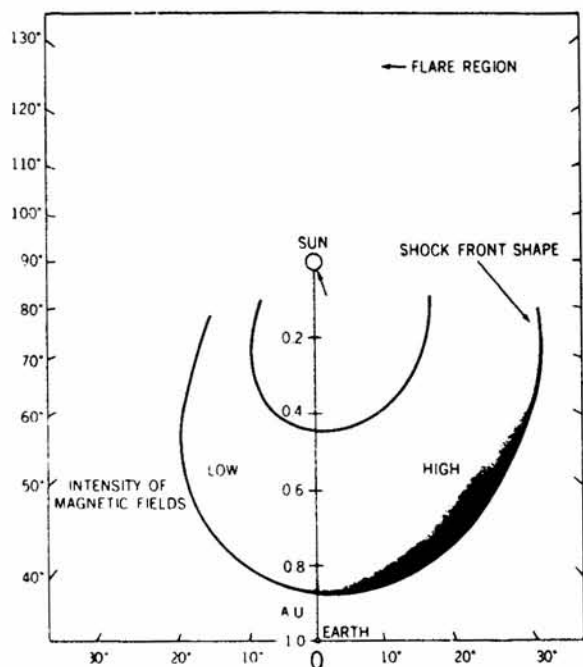


Fig. 7—Estimated shape of expanding flare ejecta near the earth's orbit (Magnetic field intensity is not uniformly distributed in the flare ejecta)

Table 1—Flare-Associated Emissions and Related Geophysical Phenomena

Flare-associated emissions	Geophysical phenomena
X-ray burst ($\lesssim 5 \text{ \AA}$)	SID SWF SEA SPA SCNA sfe
EUV burst	SFD Δf_oF2 increase
Solar cosmic rays (MeV-energy)	PCA
Flare-ejecta	Geomagnetic storm

front of those disturbances as mentioned above. This situation is shown in Fig. 7, which suggests that the cut-off efficiency of galactic cosmic rays from reaching the earth is dependent on the location of the earth within these bottle-like flare-ejecta.

In this section, we have given a review on geophysical disturbances associated with solar flares. These disturbances are detected through the two distinct media; one of them is related to the ionospheric variation, while the other is communicated through the magnetospheric medium. The relationships between solar and geophysical phenomena are summarized in Table 1. This table shows what sorts of solar emissions are responsible for various geophysical disturbances.

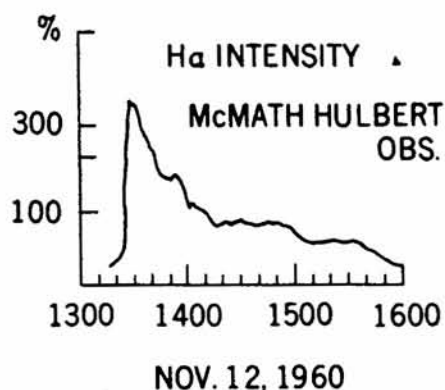


Fig. 8—The time-profile of the H_{α} line brightness

3. Nature of Solar Flares and Associated Emissions

It is known that, as shown in Figs. 1 and 2, solar flares produce various geophysical disturbances. In order to understand these disturbances in greater detail, therefore, it is necessary to investigate the nature of solar flares and associated wave and particle emissions. In this section, we shall, therefore, give a review on the observed characteristics of solar flares and associated phenomena, and then describe the relationships between the development of flares and various emissions associated with flares. Finally, the emissions responsible for geophysical disturbances as mentioned in Section 2 will be considered.

Solar flares are the phenomena in which some areas on the solar disk suddenly become relatively brighter with respect to the hydrogen Balmer alpha line intensity. These areas are sometimes located in or near the sunspot groups, while some flares occur in the plage or prominence regions. They are respectively called: (1) sunspot, (2) plage and (3) prominence flares⁴⁷. Sunspot flares are most important for the generation of various wave and particle emissions which produce geophysical disturbances. In general, spectral lines like the H_{α} one are observed as the Fraunhofer lines for the quiet sun. When flares occur, the absorption for these lines are reduced and hence the intensity of the H_{α} emission, increases in comparison with that for the quiet condition. At first, this increase rapidly goes on and then the H_{α} brightness reaches maximum during a few minutes. Later on, this brightness gradually decreases exponentially to be recovered to the state before the occurrence of flares. The time-profile of the H_{α} brightness is shown in Fig. 8. While the brightness is rapidly increasing, the area of the H_{α} brightening expands rapidly in or above the sunspot group, and later covers a large area over this group, as shown in Fig. 9. Filamentary structure of the brightening area suggests that the H_{α} brightening tends to occur along or across the magnetic lines of force rooted from the sunspot group.



Fig. 9—The H_{α} brightening area for a fully developed solar flare on 17 July 1959 (This area covers the most part of sunspot umbral regions)

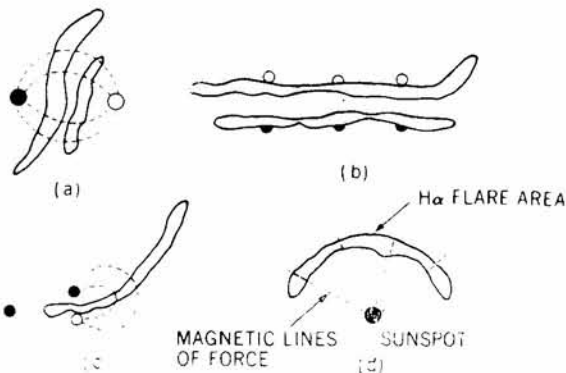


Fig. 10—Relation between sunspots and the H_{α} brightening areas.⁴⁸

By studying the relation between sunspots and H_{α} brightening areas, Kiepenheuer⁴⁸ has obtained the result as shown in Fig. 10. This figure indicates that the formation of these H_{α} brightening areas is strongly controlled by the locations of sunspots. Since the generation of sunspots is closely related to the behaviour of magnetic fields in the solar photosphere, the location of the H_{α} brightening areas also seems to be connected with the magnetic configuration in and near the sunspot group. As indicated by chain lines in Fig. 10, magnetic field lines tend to be across these brightening areas. Since flares are observed in the chromosphere or the lower corona, these field lines seem to extend into these atmospheric regions

and then control the formation of the H_{α} brightening regions near the photospheric surface.

It seems that solar flares are triggered in the region where magnetic fields along the line of sight are null, i.e. the magnetically neutral layers or points^{49,51}. These regions are sometimes generated in sunspot magnetic fields. Although there exist serious theoretical problems to explain magnetic dissipation in the neutral layer or point, it is thought that solar flares occur as a result of this dissipation due to sunspot field annihilation^{47,47,52,53}. At present, it is known that the sunspot groups of δ -type are very active in producing solar flares⁵⁶⁻⁵⁸. These sunspot groups generally show unusual magnetic configuration such that north and south polarity regions appear together in the same main penumbral regions^{56,57,59,60}. Furthermore, the distribution of these two magnetic polarities is unusual for sunspot groups which produce proton flares^{57,61-63}. The origin of this distribution seems to be related to the rotating motion of sunspot axis⁶⁰. By taking into account the twisting motion produced by this rotating motion, the mechanism of solar flares is investigated^{57,64}. Thus it is very important to study the detailed structure and variation of sunspot groups in reference to magnetic configuration.

Table 2—Developmental Pattern of Solar Flares and Associated Emissions

<i>Preflare state</i>	
H_{α} plage bright spots	
Birth of satellite sunspots	
Peculiar distribution of sunspot magnetic configuration	
Activation of dark filaments	
Enhancement of soft X-rays and microwave emissions	
<i>Explosive phase</i>	
Sudden expansion of the H_{α} bright area	
Sharp increase of H_{α} brightness	
Microwave bursts (often associated with type III bursts)	
Hard X-ray bursts	
Moreton waves	
Acceleration of high-energy particles	
(Solar cosmic rays, relativistic electrons)	
<i>Main Phase</i>	
Blast waves and the ejection of magnetic clouds (or flare-ejecta)	
Radio bursts of spectral type II and IV	
Soft X-rays	
Ejection of accelerated high-energy particles	
<i>Late Phase</i>	
Stationary continuum storm	
Flare nimbus	
Loop prominence system	

Solar flares are generally associated with various wave and particle emissions; gamma-ray, X-ray and EUV bursts, radio bursts of spectral types II, III, IV and V, the Moreton waves, shock waves, microwave radio bursts, solar cosmic rays, magnetic bottles or clouds and flare ejecta. Not all flares are accompanied by these emissions, but a flare of importance 4B, for instance, produces the most emissions described above. These emissions are not produced simultaneously with the start of flare. It is now known that a typical flare develops through three distinct phases defined as the explosive, main and late phases^{4,65}. During each phase, several proper emissions are generated as indicated in Table 2. It is known that, within a few days before the occurrence of a flare, some active phenomena are observed in the sunspot group where this flare is triggered; they are filament activation, plage brightening, the flux increase of microwave and X-ray emissions⁴. These phenomena are important as a precursor foregoing the onset of flares. When the proton Flare Project was planned to study the prediction and development of proton flares in the IQSY committee, the observation of

those phenomena as mentioned above was extensively done to find out what was going on before the occurrence of proton flares⁶⁶.

Analyzing the phenomena associated with flares, it seems possible to classify flares into three different types, as shown in Fig. 11: they may be called (1) SWF type, (2) geomagnetic storm type, and (3) solar proton type. These classifications were first done by Sinno and Hakura^{67,68}. This result indicates that the time-profile of radio bursts for several discrete frequencies is a measure for geophysical phenomena observed at the earth; for example, SWF type of flare does not produce geomagnetic storm nor high energy solar cosmic rays. As shown in this figure, this flare only accompanies SID phenomena as SWF. A flare of geomagnetic storm type (Fig. 11-2) is associated with geomagnetic storm, but does not produce solar cosmic ray event other than S type event. It is noted that an associated SWF does not show a sudden onset. The third solar proton type of flare is accompanied by MeV-BeV solar cosmic rays, geomagnetic storm and sudden-onset type SWF. Therefore, we may say that the developmental pattern of

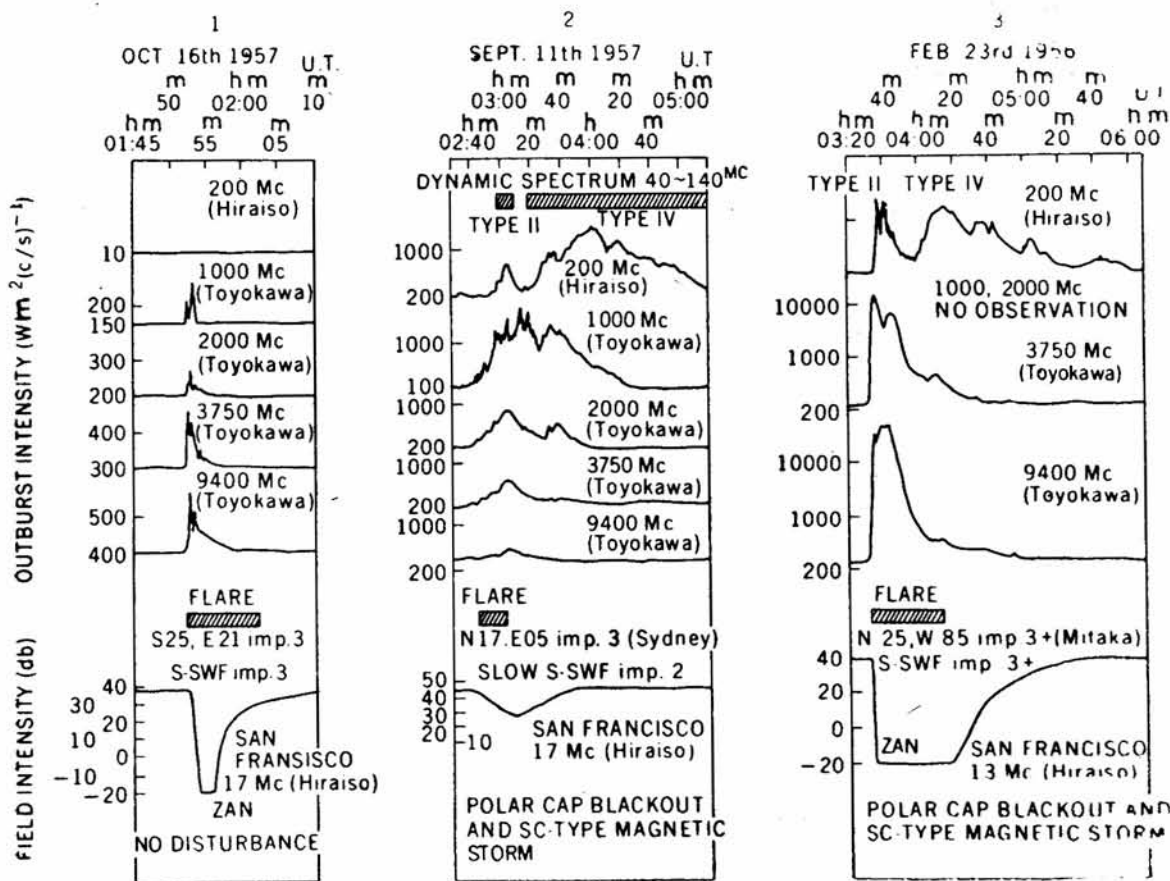


Fig. 11—Three types of the development of solar radio bursts and SWFs associated with solar flares: (1) SWF type, (2) geomagnetic storm type and (3) solar proton type¹³

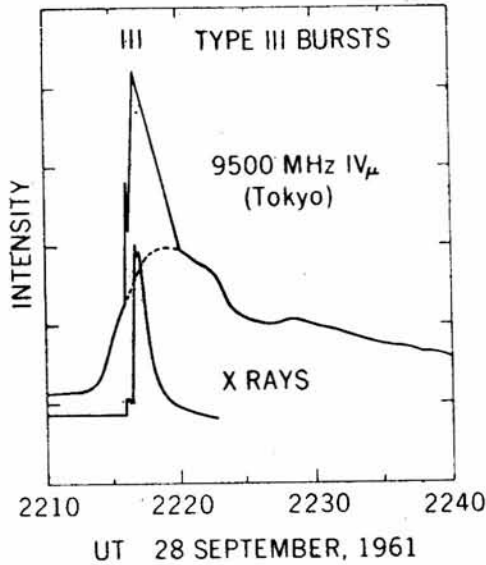


Fig. 12—The time profiles of both microwave and X-ray bursts and associated type III radio bursts⁷³

radio burst is very useful to estimate what disturbances are produced on the earth after the onset of flares.

Although the characteristics of solar flares and associated radio and SWF phenomena are shown to indicate the developmental pattern of radio bursts and SWFs, these flares are also associated with X-ray bursts, as expected from the observations of SWFs. In fact, microwave bursts are usually accompanied by X-ray bursts⁶⁹⁻⁷¹ (Fig. 12). Association of these bursts with type III radio bursts at metric frequencies is well known, as shown in this figure⁷²⁻⁷⁴. Fig. 11 also indicates that the time-profiles of microwave emissions are similar to those for SWFs pattern. This fact suggests that the mechanism of X-ray emissions by flares is closely connected^{72,75,77-79} with that of microwave emissions^{70,73,75-77}. Since it is known that these two emissions are, respectively, generated by bremsstrahlung and gyro-synchrotron mechanisms from high energy electrons accelerated in flares, we are able to interpret⁷⁸⁻⁸⁰ systematically these emissions by considering the energy spectra and a number of these electrons in the flare regions^{76,77-80}. In order to understand SID phenomena in greater detail, therefore, we have to know the physical mechanism which takes place in the flare region during each phase as summarized in Table 2. As shown in Fig. 11, SWFs always start simultaneously with the start of microwave radio bursts. Furthermore, the developmental patterns of SWFs are similar to those of microwave bursts⁸¹ at 9400 MHz.

We shall consider the developmental pattern of a major solar flare and associated wave emissions. This consideration seems to be important for the under-

standing of the relationships between flare phenomena and geophysical disturbances.

3.1. Wave Emissions and the Developmental Pattern of Solar Flares

The development of a typical flare consists of three different phases as described in Table 2. As shown in Fig. 8, the H α line brightness rapidly increases for the first few minutes. During these times, various wave emissions begin to be radiated from the flare region. The period for this brightness to increase sharply is now defined as the explosive of flash phases^{82,83}. Because various wave emissions from gamma rays to radio waves are observed almost simultaneously during this phase, it seems that the release of flare-energy to these emissions occurs very rapidly with the start of this phase by means of some mechanism though still not known very well. The transfer of this energy to various modes of energy consecutively occurs to make the main and late phases develop. Thus, the most important phase is the explosive phase; however, we do not know yet the mechanism of the storage and release of flare-energy in sunspot groups in spite of our effort to find out the cause of flares^{4,53,84,85}. A current review on the origin of solar flares is described in Tandberg-Hanssen⁴⁷.

While the H α line brightness is rapidly increasing during the explosive phase, microwave (M-W) and hard X-ray bursts begin to be emitted. Thermal component of X-ray bursts follows hard X-ray emissions. During this phase, type III radio bursts are often observed at metric and lower frequencies. The emission

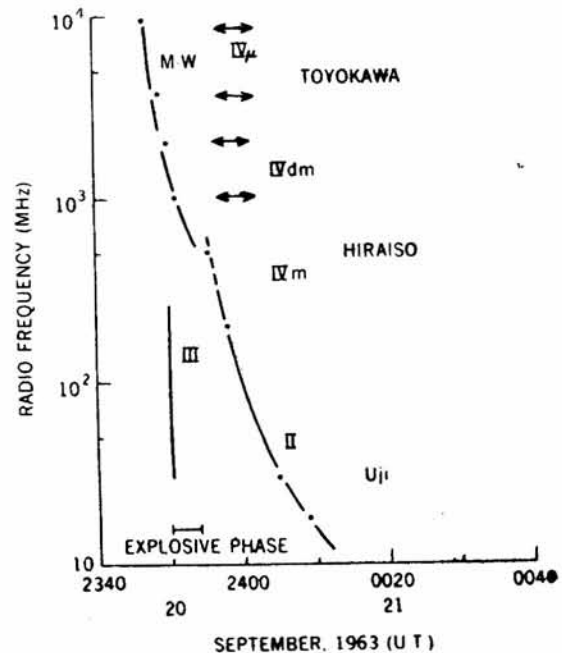


Fig. 13—Time sequence on the beginning of solar radio bursts as a function of radio frequency

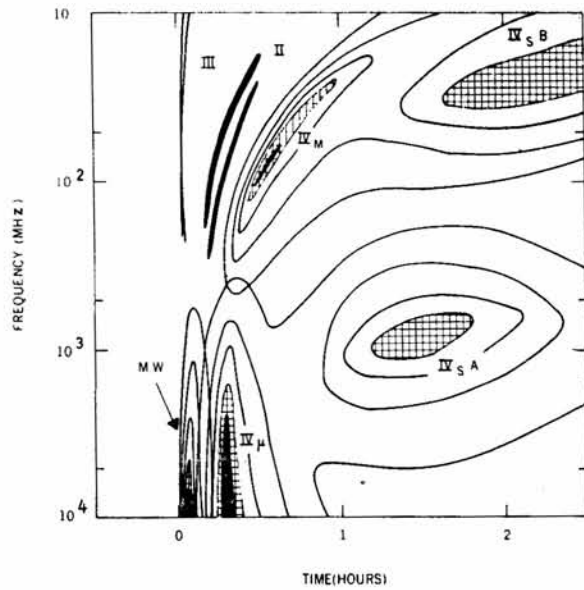


Fig. 14—A model of the development of solar radio emission associated with a major flare (Intensity is high in the dark shaded areas)

of microwave type IV bursts (IV_{μ}) also starts almost simultaneously with microwave bursts (M-W). When we plot the onset times for these radio bursts as a function of observed frequencies, the result as shown in Fig. 13 is obtained. This figure shows that, at first, microwave burst starts to be emitted at frequencies higher than ~ 500 MHz. Type III bursts at metric frequencies are associated with this microwave burst during the explosive phase. It is very difficult to find out the onset time of type IV radio bursts because forerunning microwave and type II bursts, in general, overlap type IV burst. In Fig. 13, by arrows, we only show the times for the maximum flux intensities by type IV burst at frequencies higher than 500 MHz. By schematically reproducing the dynamic spectrum of radio bursts of spectral types II, III and IV, we obtain the result as shown in Fig. 14 for the frequency range from 10 to 10^4 MHz. This figure indicates that type IV radio burst consists of several different components as IV_{μ} , IV_m , IV_{sA} and IV_{sB} . Since the classification of these components is very

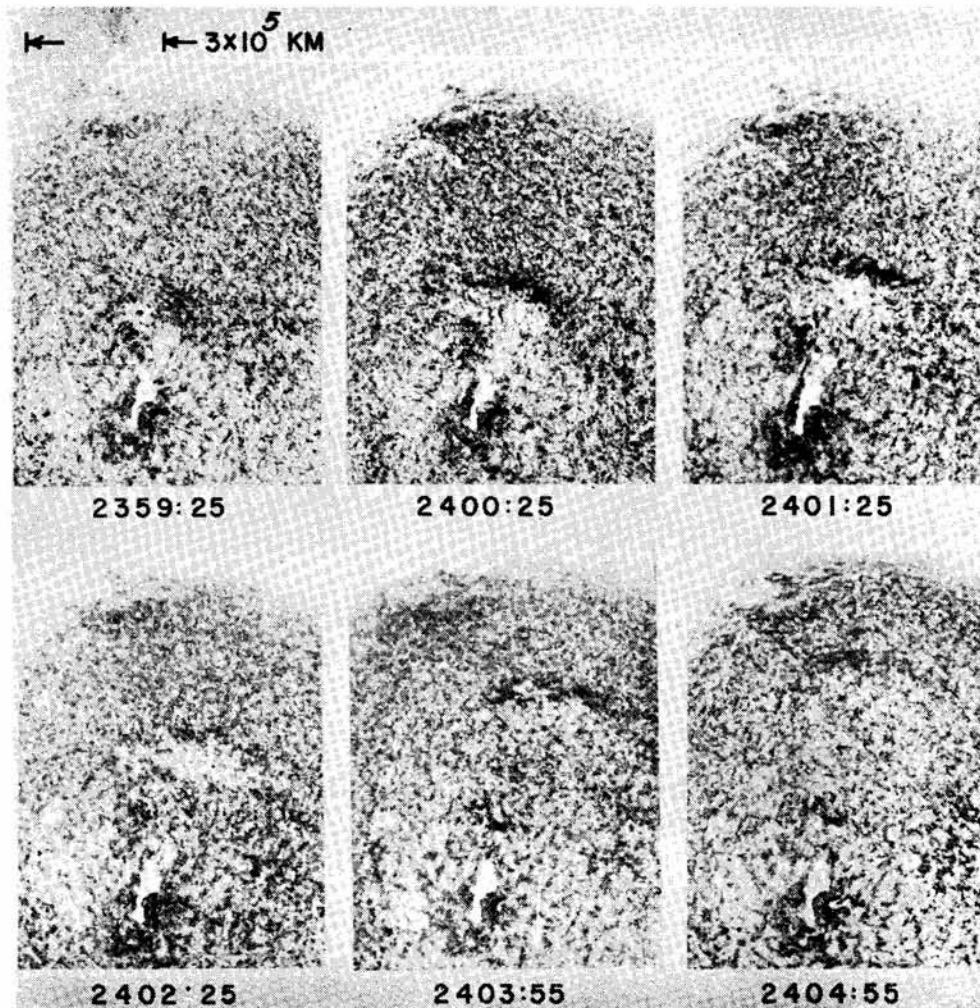


Fig. 15—Picture of the Moreton wave associated with the solar flare of 20 Sept. 1963 (after Martin and Harvey⁹⁸) (White part is the H_{α} brightening area of flare)

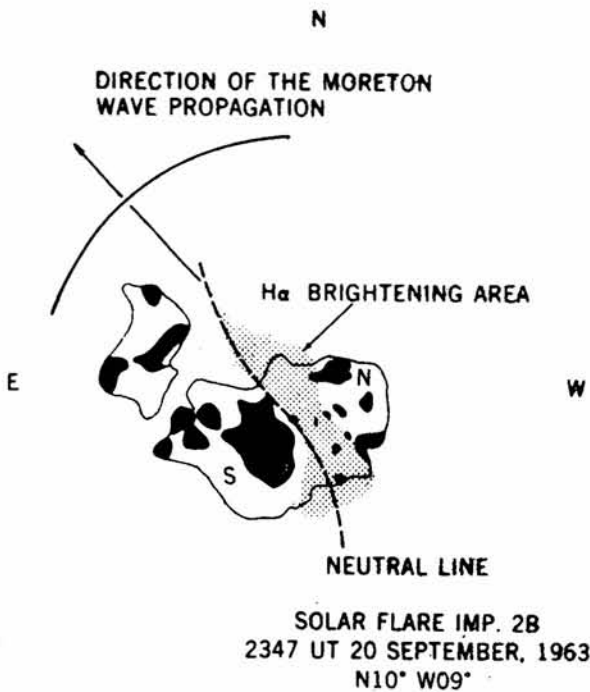


Fig. 16—Relation of the sunspot structure with the propagation direction of the Moreton wave in the case of the 20 Sept. 1963 flare (A chain line indicates the magnetically neutral line)

different from one author to another, the result shown here must be considered as one of these classifications (see the works in Ref. 86-90). As shown in this figure, microwave type IV burst ($IV\mu$) starts before the emission of microwave burst (M-W) ceases.

Moreton⁹¹ observed the surface waves propagating away from the flare region as being mainly along the photospheric surface. These waves are now known as the Moreton waves. In association with the solar flare of 20 September 1963 described in Fig. 14, a beautiful picture was taken^{92,93} for this wave as shown in Fig. 15. This result shows that this wave propagated into some limited direction within $\sim 90^\circ$. When we compare this observation with the sunspot configuration and other data, we can see that this wave propagated out of the flare region along the magnetic axis which was almost coincident with the magnetically neutral line shown by a chain line in Fig. 16. A wave front is indicated in this figure, which has been deduced from the picture shown in Fig. 15. These Moreton waves are also generated during the explosive phase. Hence the origin of these waves seems to be related to the process for flare-energy to be released, but the reason why these waves do not propagate in every direction from the flare region has not been found yet. Recently, Uchida *et al.*⁹⁴ have theoretically calculated the motion of shock wave fronts generated by flares in order to

explain the relation between the Moreton waves and the shock waves responsible for type II radio bursts at metric frequencies. As considered by Sakurai^{95,96}, these shock waves are also generated during the explosive phase of flares.

The time variation of hard X-ray emission intensity is similar to that of microwave emission (see, Fig. 11). Fig. 17 indicates that the profile of solar X-rays >80 keV observed by the IMP-3 satellite is almost the same as the intensity-time profile of microwave burst⁷¹ at 17,000 MHz. This suggests that the source for these two emissions must be the same^{75,77-80}. Because it is known that these X-ray emissions ($<1\text{\AA}$) are responsible for the production of SIDs, these solar X-rays associated with the flare of 7 July 1966, as shown in Fig. 17, must have produced SIDs. Hakura⁹⁷ found that the time variation of SCNA observed at Penticton, Canada, is almost the same as that of soft X-ray burst ($<14\text{\AA}$), which was reported by Van Allen and Ness⁹⁸. The intensity-time profile of this soft component is not fully equal to that shown in Fig. 17, but the starting times of both emissions are almost equal to each other. However, the time for intensity decrease is usually longer for soft component than for hard component because the former is generated in association with the thermalization of flare plasma⁹⁹. These two components have been directly found by using the observation of several

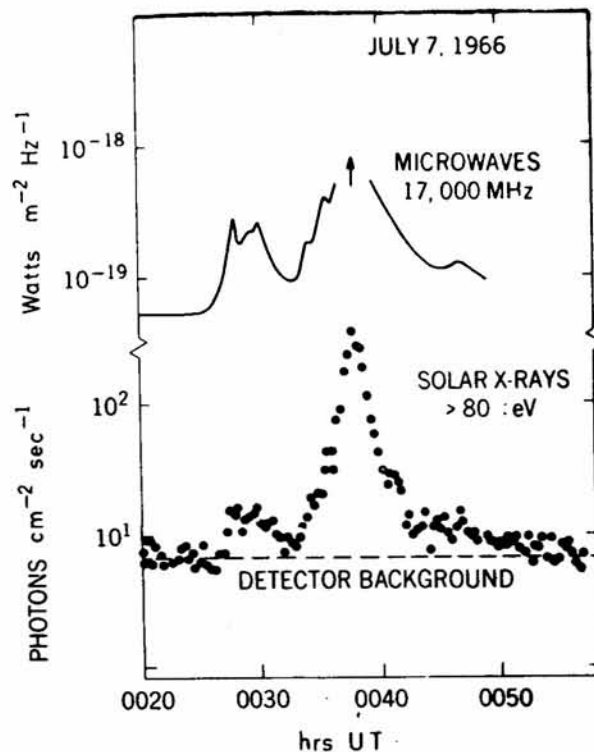


Fig. 17—Intensity-time profiles of microwave and hard X-ray bursts associated with the flare of 7 July 1966⁷¹

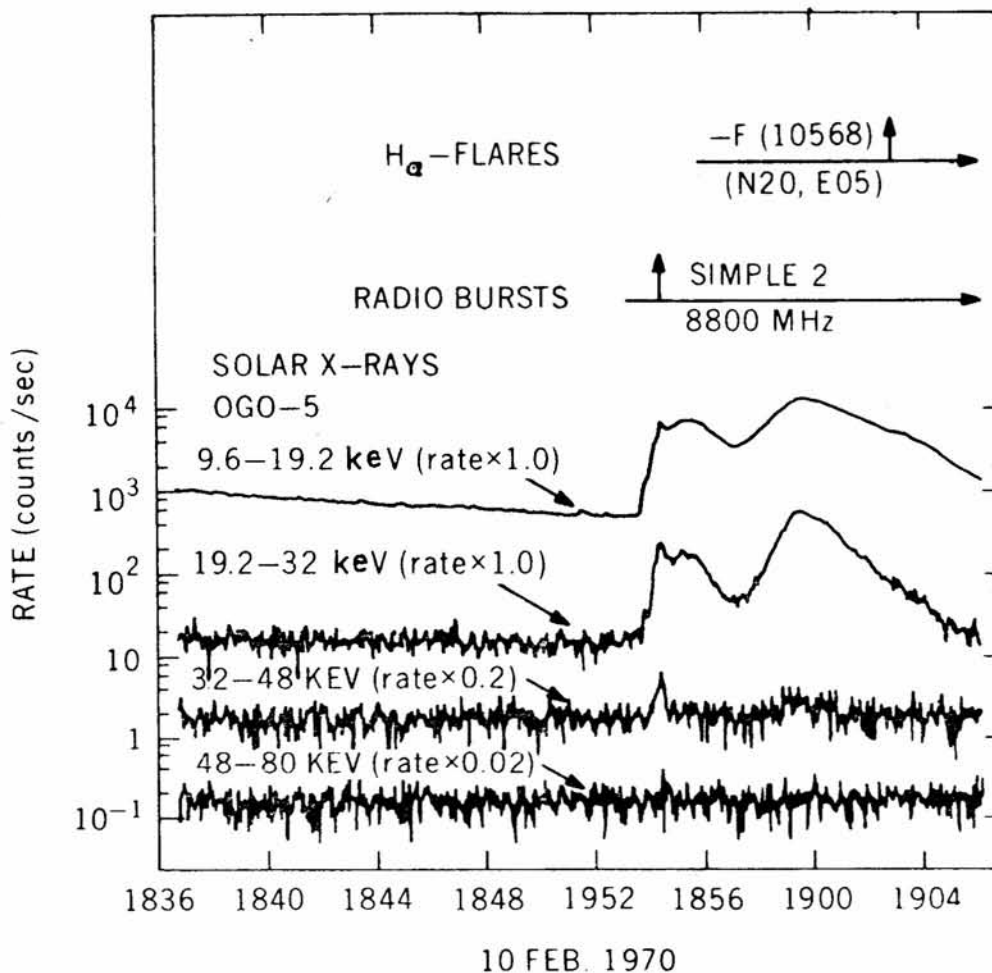


Fig. 18—Developmental patterns of X-ray bursts as observed by different energy channels¹⁰⁰

channels for energy by the OGO-5 satellite (Fig. 18)¹⁰⁰. The first peak in this figure is generated by non-thermal emissions, while the second peak around 1900 UT are due to thermal emissions, which are mainly responsible for the production of SID phenomena. In general, the first peak intensity is very low in comparison with the second peak intensity, and the duration is much shorter for the first component than for the second component^{101,102}. This tendency is also seen in microwave radio burst (see Fig. 17).

Chupp *et al.*¹⁰³ first observed gamma-ray bursts from the solar flares which occurred in August 1972. Since several characteristic gamma-ray line emissions were observed for these flares, a number of high energy MeV protons must have been produced to make nuclear interactions possible with ambient nuclei in the flare region. This means that these high-energy nuclear particles are accelerated during the explosive phase of flares. Since the mechanisms of X-ray and radio bursts as mentioned earlier are explained by taking into account the interaction of high energy electrons (keV-MeV) with ambient

plasmas and sunspot magnetic fields, respectively, these electrons must also be generated during the explosive phase. Therefore, we may say that the acceleration of high energy protons, heavier nuclei and electrons is very important to produce various wave emissions as mentioned earlier. We have now evidence that these high energy particles are generated during the explosive phase of flares^{95,104}.

The expansion of shock waves from the region where a flare triggered, is a good measure for the start of the main phase of flares¹⁰⁵. This phase seems to be initiated by the outward movement of type IV radio sources from the flare region. This movement usually follows the expansion of shock waves in the solar atmosphere, but the speeds of these sources and waves are generally not equal to each other^{41,106}. The sources of type IV radio bursts at metric frequencies (IV_m in Fig. 14) generally move outward with speed of several hundred km sec⁻¹, which is always lower than that of foregoing shock waves. Because the source for type IV_μ burst does not move out of the flare region, this source seems to be independent of

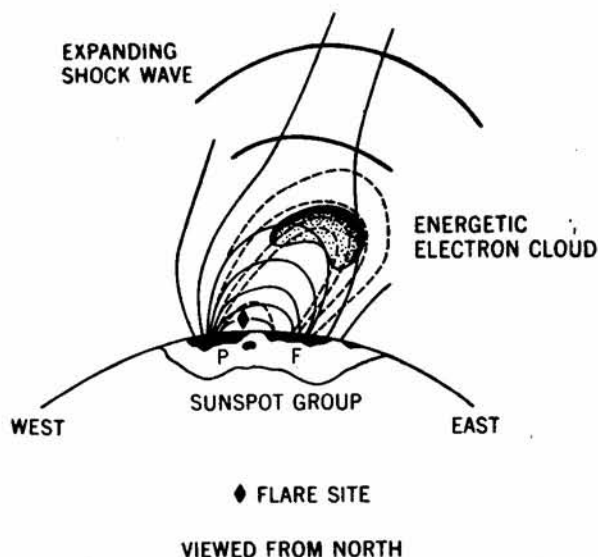


Fig. 19—Motion of magnetic bottle and forerunning shock wave above the flare region¹⁰⁹ [Trapped electrons are identified as the source of metric type IV burst (IVM)]

the source for type IV μ burst^{76,90,107}.

The generation of the shock waves mentioned above may be related to the mechanism which triggers the onset of flares due to the sudden release of flare-energy stored in sunspot magnetic fields. This energy is transferred to particle energy through the acceleration processes of protons, heavier nuclei and electrons during the explosive phase. Particles thus accelerated are first trapped by sunspot magnetic fields in or near the flare region, and then these particles transport these fields whenever the kinetic pressure of the former finally becomes higher than the tension of these fields. Thus magnetic bottles or bottle-like structures are formed by high energy particles accelerated in flares; they move outward through the solar atmosphere while emitting radio bursts identified as type IV μ bursts

It is known that the magnetic bottles as the moving metric type IV sources are preceded by the moving sources for type II bursts identified as shock waves (see Fig. 14). Sakurai^{108,109} has found that the direction of motion of these bottles is not in the meridian plane across the flare region, but 10-30 degrees east of this plane, as shown in Fig. 19. As the radioheliograph observations show that the shock waves generally propagate along the magnetic field lines in the coronal region⁴², the moving pattern of the bottles is somewhat different from that of these waves after ejection from the flare region; the bottle tends to transport field lines with energetic electron cloud, which is the source of type IV μ bursts. These electrons emit radio waves identified as these bursts by gyro-synchrotron mechanism due to their interaction with the field lines constituting the bottle.

Shock waves expand farther into the envelope of the sun and then often into interplanetary space. These waves are thought to sometimes become the interplanetary shock waves, which produce SSCs on the geomagnetic field.

During the initial stage of this main phase, the heated plasmas in the flare region would be thermalized to be 10^6 - 10^7 degrees in temperature. These plasmas are capable of producing soft X-ray and microwave radio G-R-F emissions^{110,111}. SID phenomena are associated with this X-ray emission. It is interesting to note that there seems to exist two types of this thermalization process⁸¹ as shown in Fig. 20; the one is sudden-onset type, whereas the other is gradual-onset type.

Later on, stationary radio sources are formed in the solar atmosphere, as shown in Fig. 14. When they are produced above the flare region, it is said that the late phase of a flare starts, because all violently disturbed phenomena are not observed in this phase. Metric continuum radio source (IV μ B) is often identified as type I noise source. The emission mechanism for these two sources seems to be the same¹¹²; they are generated by some plasma processes related to electron plasma oscillation. Sometimes, stationary loop prominences are formed^{113,114}. These prominences seem to be produced as a result of storage of high energy particles in the flux tubes of sunspot magnetic fields in or near the flare region^{115,116}.

These particles are gradually emitted into outer space for the period from several hours to a few days¹¹⁷⁻¹¹⁹. The duration of this period seems to be related to the magnetic configuration of the flare region. Therefore, the duration of continuum emissions IV μ A and IV μ B is also dependent on this

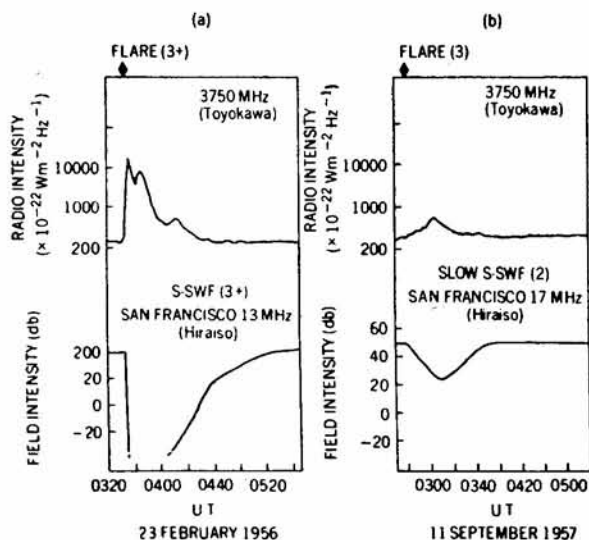


Fig. 20—Two distinct developmental patterns of SWFs (They are very similar to those for microwave radio bursts⁸¹)

configuration because these emissions are produced by energetic electrons trapped by sunspot magnetic fields.

3.2. Particle Emissions

High energy particles are mainly accelerated during the explosive phase. Initially, keV electrons are accelerated suddenly during 1-10 seconds immediately after the onset of this phase. However, the main part of high energy particles, MeV-BeV protons and other nuclei and relativistic electrons are accelerated during the explosive phase which continues for a few minutes^{95,104,120,121}. The acceleration mechanism has not been fully understood for these particles, but Sakurai^{29,122} has shown that the Fermi acceleration works efficiently to produce high energy particles. General theory of particle acceleration is discussed in several works (Ref. nos. 123-128).

The ejection of the main part of these particles into outer space is associated with the expansion of magnetic bottles¹²⁹. Therefore, it seems that these particles are emitted into interplanetary space before the end of the explosive phase^{120,130}. In August 1972, BeV solar cosmic ray events were observed three times, which were produced by flares which occurred in the active region McMath No. 11976. These BeV events are, however, not so often produced during the solar activity cycle. It is estimated that these events occur about 20 times for one cycle^{4,128}. Since these events do not produce any geophysical disturbance, we shall not consider them hereafter. The readers who are interested in this subject may refer to the literature in reference numbers: 4, 82, 131-135.

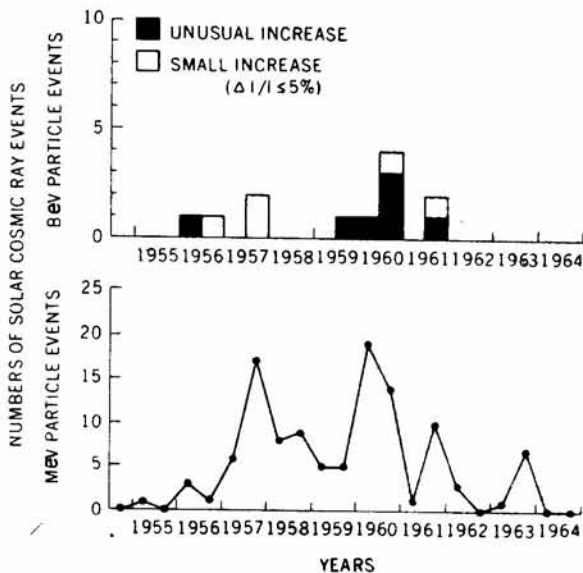


Fig. 21—Long-term variation of the occurrence number of solar proton flares, BeV and MeV, for the solar cycle No. 19 (after Sakurai¹⁴¹)

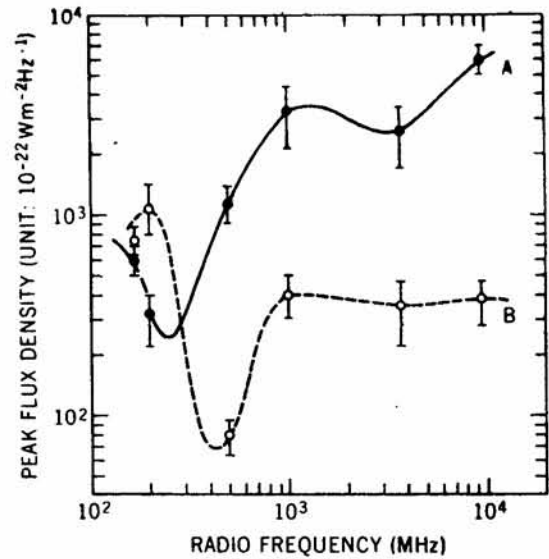


Fig. 22—Two representative peak flux spectra of type IV radio bursts (The spectra A are associated with flares which produce F and F* type of solar proton events, whereas the spectra B are related to those for S type events¹³⁹)

The MeV solar cosmic ray events were discovered by Bailey¹³⁶ from the analysis of the HF forward scatter propagation in the high latitude regions of the earth. He found that the wave intensity decreased while MeV solar protons and other nuclei were bombarding these regions. This indicated that the wave energy is heavily absorbed in the region where the electron density is increased by the excess ionization of the lower ionosphere due to their bombardment^{16,136-138}. It is now known that these MeV events occur more frequently than the BeV events mentioned above; their occurrence frequency is well related to the phase of the solar activity cycle¹³⁹⁻¹⁴¹, as shown in Fig. 21. It seems likely that BeV events do not occur during the maximum phase of this cycle^{42,143}.

Hakura and Goh⁴⁴ first attempted to study the relation of these MeV events with solar phenomena; they found these events were always associated with the flares accompanying type IV radio bursts of wide frequency band. This result indicates that the generation of MeV solar cosmic rays is closely connected with that of relativistic electrons.

Since these MeV particles ionize the region of the upper atmosphere 50-100 km high above the polar caps, the ionosondes and the riometers on the polar regions are able to indirectly detect the bombardment of these particles as the ionospheric absorption of transmitted waves and cosmic background noises. These absorption phenomena are now called the polar cap absorptions (PCA). We have shown in Fig. 3 that there exist several types of these absorption (PCA) events. When we compare these types with the

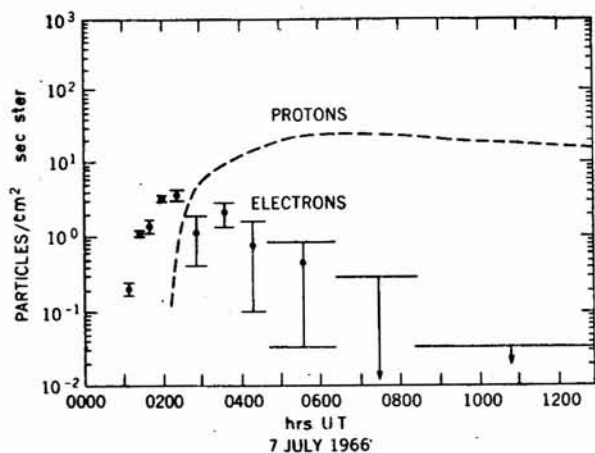


Fig. 23—Satellite observation of MeV electrons associated with the solar flare of 7 July 1966 (Proton data are also shown) (after Cline and McDonald¹⁴⁸)

peak flux spectra of type IV radio bursts, we obtain the result that the spectra indicated with A in Fig. 22 are always associated with the PCA events of F or F* type, whereas the spectra shown by B are accompanied by S type events¹⁴⁵. The importance of A type spectra for the generation of solar cosmic rays has been pointed out by Castelli *et al.*¹⁴⁶⁻¹⁴⁷, who called them the U-shape spectra.

Analyzing the IMP-3 satellite data, Cline and McDonald¹⁴⁸ have shown that MeV electrons are also ejected by flares which produce MeV solar cosmic rays. The first observation of these electrons was done by Meyer and Vogt¹⁴⁹ by means of the detectors on-board balloons. Fig. 23 shows the time variation of MeV electron flux from the sun with MeV protons as observed by the IMP-3 satellite. These electrons seem to be emitted from the flare region, although the main part of these electrons seem to be trapped by sunspot magnetic fields as emitting type IV radio bursts. The direct observation of these electrons has proven that the source of type IV radio bursts is identified as the MeV electrons produced in flares. This idea was first put forward by Boischoit and Denisse¹⁵⁰, but, for many years, no direct evidence had been obtained. As Sakurai¹⁵¹ has shown, all of MeV electron events detected by satellites near the earth are associated with MeV solar cosmic ray events. This result indicates that protons and heavier nuclei are accelerated together with electrons to MeV energy in flares. It seems that these electrons sometimes invade the polar cap regions and ionize atmospheric constituents over there²⁶.

Van Allen and Krimigis¹⁵² first reported that solar flares of minor importance produced > 45 keV electrons. Since most of these flares do not produce dis-

tinguished SID phenomena at the earth, the acceleration of these electrons is not related to the large-scale disturbances associated with solar flares. However, we know that these flares are usually accompanied by impulsive X-ray and microwave bursts of short duration for a few minutes at most and type III radio bursts^{74,153,154}. These X-ray emissions often produce small SID phenomena characteristically different from those as shown in Figs. 11 and 21.

Magnetic bottles are often ejected into the envelope of the sun. While expanding there, these bottles push solar plasmas located above the flare region out to the outer space. These plasmas seem to be identified as the flare-ejecta which propagate into interplanetary space. It is thought that the helium enriched shells are formed at the front of these ejecta^{155,156}. Since the thickness of these shells observed at the earth's orbit is dependent on the longitudinal position of parent flares (Fig. 24), the

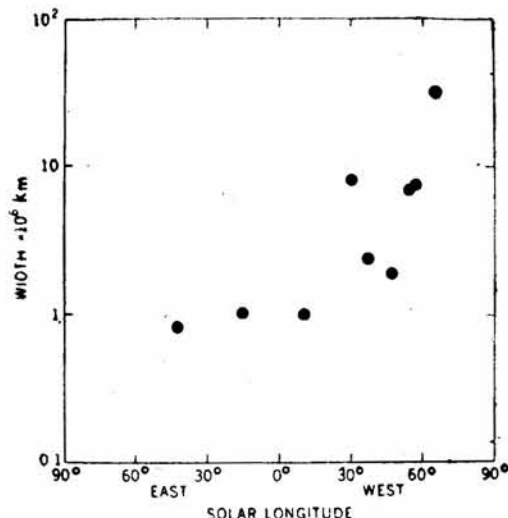


Fig. 24—Dependence of the thickness of helium-enriched shells observed at the earth's orbit on the longitudinal position of associated flares

Table 3—Particles Accelerated in Solar Flares and Related Solar and Geophysical Phenomena

Solar particles	Solar phenomena	Geophysical effects
keV electrons	Type III bursts Hard X-ray bursts	
MeV electrons	Microwave bursts Type IV bursts	PCA
MeV-BeV protons and heavier nuclei	Solar cosmic rays Gamma-rays White light emissions	PCA
Heated flare plasmas	Thermal X-rays Microwave bursts	SID

expansion of these shells also seems to occur anisotropically in the space between the sun and the earth³⁸. However, we do not know yet the mechanism of such expansion of these shells in interplanetary space. It seems that this expanding mode is causally related to the propagation pattern of inter-planetary disturbances generated by flares.

3.3. Flare Development Related to the Emissions Described in 3.1 and 3.2

So far we have considered both wave and particle emissions by using observed results. As shown in Section 3.1, the development of a major solar flare consists of three distinct phases: the explosive, main and late phases. Various emissions are generated during the development of flares, but it seems that they are properly associated with one of these three phases. We summarise these associations in Table 3 in reference to the nature of these emissions which is related to high energy particles accelerated in flares. Since the cause of all wave emissions is explained by taking into account the action of these high energy particles in the flare region, it is important to know what type of particles is responsible for those wave emissions. These informations, furthermore, are very useful to study SID phenomena by considering the characteristics of solar wave emissions. They may make it possible to predict the occurrence of SIDs and geomagnetic storms. It is, therefore, important to investigate the mechanism of particle generation in solar flares.

The number and other characteristics of energetic particles responsible for wave emissions from flares are summarized^{78,84} in Table 4. The energy expended by these particles must be supplied in the region where solar flares occur. It is known that the most flare-energy is transferred to optical emissions and flare-ejecta, the energy of which amounts to about 10^{32} ergs. When we consider the total amount of flare-energy released in a major flare to be several times^{4,84,157} of 10^{32} ergs, the energy that flare-ejecta shares and its transport mechanism must be understood in order for the mechanism of flares to be understood. At present, it is thought that the flare-energy is supplied by the annihilation of sunspot magnetic fields, but we have not succeeded in explaining the mechanism of flares^{4,53,86}.

It seems better to summarize the relationship between flare-associated emissions and geophysical phenomena (Table 5). They seem to give an important information on the cause of these phenomena.

4. Interpretation of Flare-Associated Geophysical Disturbances

We shall consider geophysical disturbances by

taking into account the observed results on flare-associated emissions. As summarized in Table 5, it is known what type of solar emissions produces proper disturbances at the earth; wave emissions are mainly responsible for SID phenomena, whereas particle

Table 4—Flare Energy and Flare-Associated Particles

	Number	Mass	Energy (ergs)
H α			10^{31}
Total line emission			5×10^{31}
Continuum emission			8×10^{31}
Total optical emission			10^{32}
Optical flare region	10^{41}	2×10^{17}	
Soft X-rays (1-20Å)			2×10^{30}
Hard X-rays			
(50 keV electrons)	10^{39}		5×10^{31}
Type IV burst			
(3 MeV electrons)	10^{33}		5×10^{37}
Type III burst			
(<100 keV electrons)	10^{35}		10^{33}
Visible ejection	10^{40}	2×10^{16}	10^{31}
Energetic protons			
(E > 10 MeV)	10^{35}		2×10^{31}
Cosmic rays (1-30 BeV)			3×10^{31}
Interplanetary blast			
wave	10^{37}	2×10^{13}	2×10^{30}
Moreton wave			$> 10^{30}$

Table 5 - Geophysical Phenomena Produced by Solar Flares

Waves	{ X-rays (Hard), < 1Å (soft), 1—100Å EUV (including He II 304Å)	SID SFD Δf_oF_2 increase
Particles	{ MeV protons and electrons Plasma clouds (flare-ejecta)	PCA Geomagnetic storm Aurorae Polar substorm
Shock waves		SSC

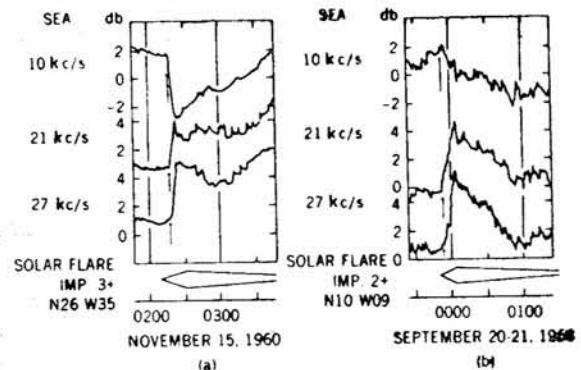


Fig. 25—Two distinct patterns of SEAs associated with solar proton flares¹⁵⁸: (a) SEA associated with BeV proton flare and (b) SEA associated with MeV proton flare

emissions produce disturbed phenomena as PCA and geomagnetic storms. By considering the results described in Section 3, we shall explain geophysical phenomena in the following.

4.1. SIDs

Fig. 20 shows that there exist two distinct patterns for SWFs. The time-profile of these SWFs is very similar to that of microwave radio bursts. This means that the emission of soft X-rays is closely related to that of these radio bursts^{81,110}. Therefore, these SWFs are explained by considering these X-ray emissions from flares.

The developmental pattern of SEAs is dependent on the characteristics of solar flares. When we use several frequencies to observe SEAs, we are able to find out such dependence^{158,159}. Two examples are shown in Fig. 25, which are associated with proton flares. The SEAs shown in Fig. 25(a) and (b) are accompanied by BeV and MeV proton flares, respectively. It is evident that the rise time is shorter for the former than for the latter. The behaviour of 10 kHz field intensity is also significantly different between them. By studying these characteristics of SEAs, therefore, we can estimate what is going on in the sun. Since the duration of these rise times is correlated with that of the H_{α} brightness increases, it is clear that the fastness of the thermalization of the flare plasmas plays a main role¹⁶⁰ for the X-ray emission from the flare region (Sakurai). It has been statistically shown that the rise time of solar X-ray emission is proportional to that of the H_{α} brightness¹⁶¹. These results suggest that SID phenomena are completely dependent on the developmental pattern of flare X-ray emissions.

The developmental pattern of SCNAs is almost the same as that of SWFs, because they are generated by the absorption of the cosmic noise due to the enhanced ionization of the ionosphere by flare-associated soft X-ray emissions. This ionization mainly takes place in the lower region of the ionosphere and so the electric current in the ionosphere of the sunlit side is sometimes enhanced by this additional ionization. This phenomenon appears as the enhancement of the Sq electric current in the ionosphere and is called¹¹ "sfe".

These SID phenomena mentioned above are generated by the enhanced ionization in the lower ionosphere, mainly, the D and E regions. However, we also know that some phenomena as SFD and the increase of foF2 are produced by the ionization increase in the lower part of the ionosphere F regions¹⁶²⁻¹⁶⁴. The ionization of this part is produced by the EUV emissions from flares. The satellite obser-

vation of the He II 304Å resonance line intensity, for instance, shows that this intensity rapidly increases with the onset of the explosive phase of flares¹⁶⁵. The continuum EUV emissions show a similar increase as does the He II 304Å intensity¹⁶⁶.

When Knecht and McDuffie¹⁶⁷ discovered the first evidence of the foF2 increase, they found that this increase is only associated with big flares which produce solar cosmic rays. Their analysis, furthermore, showed that the height where the peak frequency foF2 is observed, must be lower than 300 km above the ground. This suggested that the increase of the ionization occurs in the lower region of the ionosphere F2 region. Recent SFD observations indicate that the ionization enhancement occurs in the lower portion of the ionosphere F2 region. The study of these disturbances like SFD was also opened up by the investigation of the relation between the foF2 increase and solar proton flares.

These phenomena called SIDs are all generated by the enhanced ionization of the earth's upper atmosphere by solar X-ray and EUV emissions associated with solar flares.

4.2. PCA

Solar flares often produce MeV protons and other nuclei. These particles are later emitted from the flare region and some of them arrive at the earth and its vicinity. When they begin to interact with the geomagnetic field, their orbits start to be deflected by the influence of this field^{168,169}. As Schlüter¹⁷⁰ has shown, we can calculate these motions under the guiding-center approximation because the gyro-radii of these particles are much smaller than the characteristic scale length of the geomagnetic field¹⁷¹⁻¹⁷³. The result for these orbital motions shows that these particles can only approach the polar latitude regions, although depending on their rigidities.

Obayashi and Hakura¹⁴ studied the developmental pattern of the polar cap absorption (PCA)

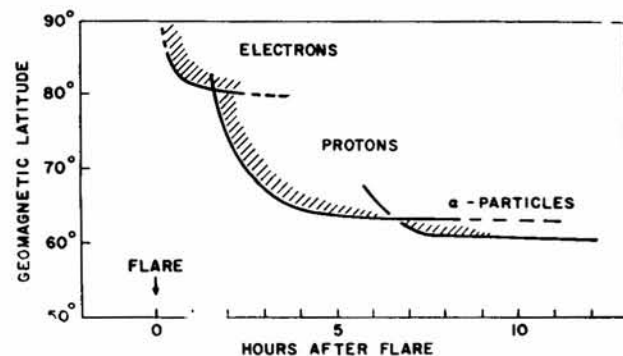


Fig. 26—Schematic representation of three phases of the development of polar cap absorption event

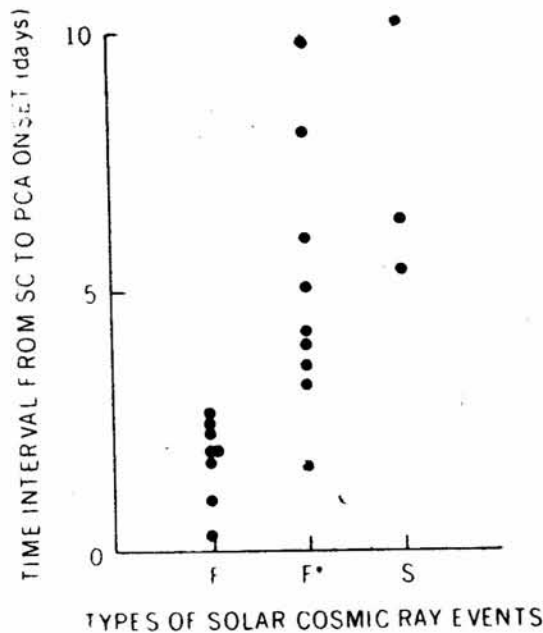


Fig. 27—Durations between foregoing geomagnetic storms and solar proton events (These durations are important in forming the developmental pattern of these proton events²⁸ as shown in Fig. 3)

produced by the invasion of MeV solar cosmic rays over the polar cap ionosphere. They found that the cut-off latitude for their invasion is usually seen around 75° N and S, but this latitude is lowered down to $\sim 65^\circ$ when the main phase of geomagnetic storms starts. This variation is related to the geomagnetic variation during storms. Hakura²⁶ found that the development of PCA consists of three distinct phases, as schematically shown in Fig. 26. At first, the invasion of MeV electrons produces weak PCA near the magnetic pole, higher than 85° N and S, which is identified as the first phase. The second and third phases are generated by the invasion of MeV protons and helium nuclei, respectively. Because of the difference of rigidities between proton and helium, the starting times and cut-off latitude for invasion are different between these two particles, as shown in Fig. 26.

Several different developmental patterns of PCA events are known (Fig. 3). It seems that the cause of these patterns is closely related to the physical condition of interplanetary space²⁸; that is, this cause is made clear when we consider the duration from foregoing geomagnetic storms to the onset of PCA events (see Fig. 27). This result indicates that, within several days after the passage of the flare-ejecta producing these storms, the distribution of the interplanetary field is so smooth that MeV solar cosmic rays can propagate almost freely without serious scattering in the space between the sun and the earth.

The access of these cosmic rays to the polar regions has been investigated by many authors^{24,27,138,174-176}. However, we do not know yet any theory capable of explaining all the observed phenomena for solar cosmic ray invasion into the polar cap regions.

4.3. Flare-Generated Interplanetary Disturbances

About 90% of solar flares associated with both type II and type IV radio bursts are followed by SSC geomagnetic storms¹⁷⁷. This shows that shock waves propagating in interplanetary space are produced by these flares.

We have known that type II radio bursts are generated by shock waves propagating through the solar coronal region^{42,178,179}. Although we do not know yet whether or not these waves are able to arrive at the earth's orbit, it is certain that some disturbances are sent out of the flare region, which can propagate through interplanetary space. It seems that these disturbances sometimes generate shock waves at the front of themselves while propagating in this space⁶. Because of the almost spherical expansion, the shock waves which produce type II bursts, would be dissipated very quickly while propagating in the envelope of the sun. However, flare-ejecta following these waves seem to generate newly shock waves somewhere between the sun and the earth. Such process seems to be repeated several times before these ejecta arrive at the earth's orbit. For this reason, we do not observe one-to-one correspondence between SSC storms and interplanetary shock waves near the earth observed by satellites¹⁸⁰.

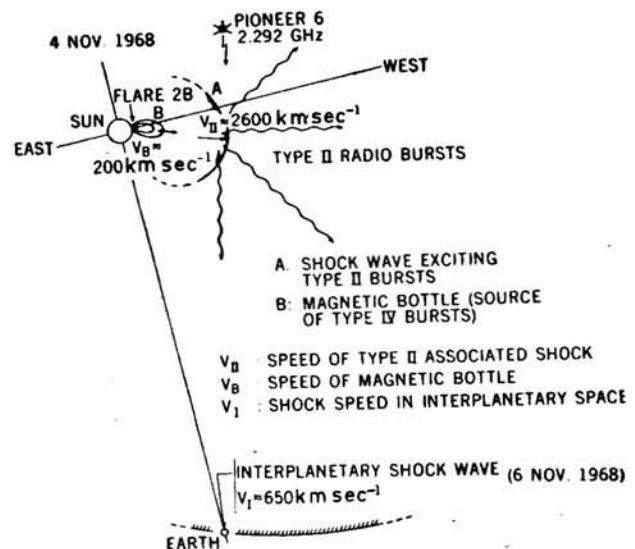


Fig. 28—Shock wave and magnetic bottle near the sun and interplanetary shock wave as produced by the solar proton flare of 4 November 1968 (Their speeds are different from each other¹⁸⁰)

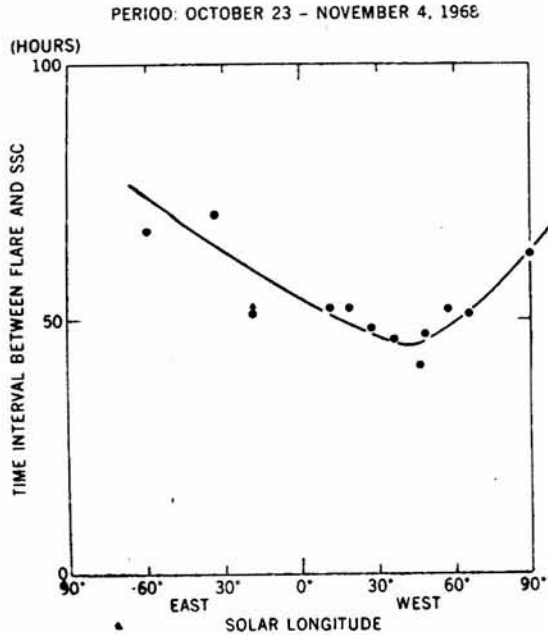


Fig. 29—Time intervals from solar flares and SSC geomagnetic storms during 23 October to 4 November 1968 (These flares occurred in the active region¹⁸⁰ McMath No. 9740)

In case of solar proton flares, however, we generally observe interplanetary shock waves near the earth. In association with the proton flare of 4 November 1968, type II bursts were observed and their characteristics showed that the radio source moved outward with the speed of about 2600 km sec^{-1} in the solar corona¹⁰⁷. Three days later, we observed the interplanetary shock wave at the earth's orbit by the Explorer 33 satellite. The mean speed of this wave was about 650 km sec^{-1} (see Fig. 28). Although we do not know whether the shock wave near the sun continued to propagate until it arrives at the earth's orbit as the shock wave mentioned above, this flare was associated with these two shock waves, one near the sun and the other at the earth's orbit. If the shock wave observed near the sun is identified with that at the earth's orbit, our result suggests that, while propagating in interplanetary space, shock waves must be decelerated highly in this space^{106,181}.

It is known that flare-generated interplanetary disturbances do not propagate spherically symmetric with respect to the flare position after ejection into outer space. Figs. 5 and 24 indicate that the propagations of these disturbances and of accompanied helium enriched shells are highly dependent on the longitudinal positions of parent flares. Sakurai¹⁸⁰ has analyzed a series of flare-generated interplanetary disturbances for the period from 23 October to 4 November 1968. During this period, more than 10 times of these disturbances were observed. By analyzing

the time intervals between flares and SSC storms, he has obtained the result shown in Fig. 29. This result shows that the minimum interval was observed when the flare occurred about 35° west of the central meridian of the solar disk. Using this result, the mean propagation pattern of the interplanetary disturbance at 1 \AA has been estimated as shown in Fig. 30. This result is consistent with that shown in Fig. 7 with respect to the shape of the disturbance. During the period mentioned above, three cases for these disturbances were identified as interplanetary shock waves¹⁰⁶.

Anisotropic propagation of interplanetary disturbances has been first suggested by Ness and Taylor³⁵ on the basis of their analysis of satellite magnetic data for the 8 July 1966 storm event. At present, we have further supporting evidence for the anisotropic propagation^{39,40}. Although it is very difficult to theoretically explain such anisotropic propagation pattern as shown in Fig. 30, these observations must be

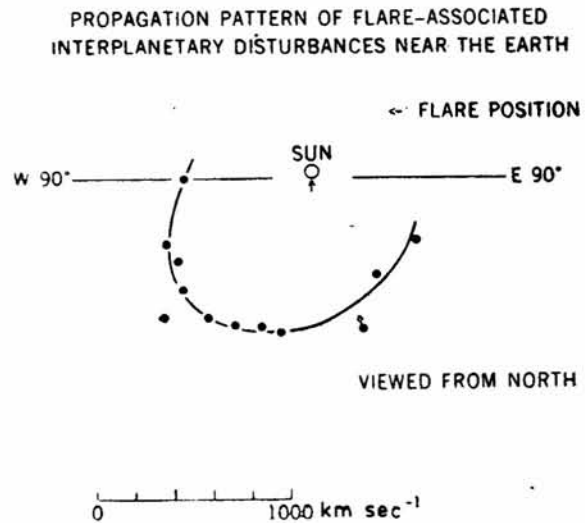


Fig. 30—An example of the propagation pattern of interplanetary disturbances associated with solar flare (This is derived from the data shown in Fig. 29)

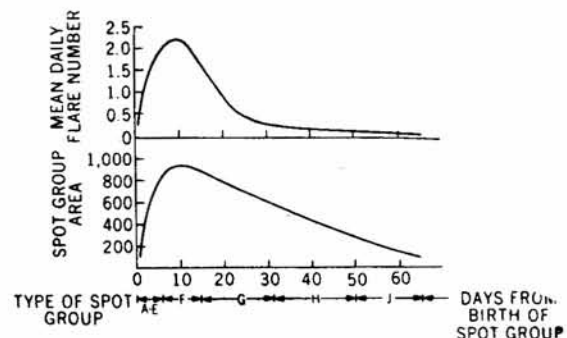
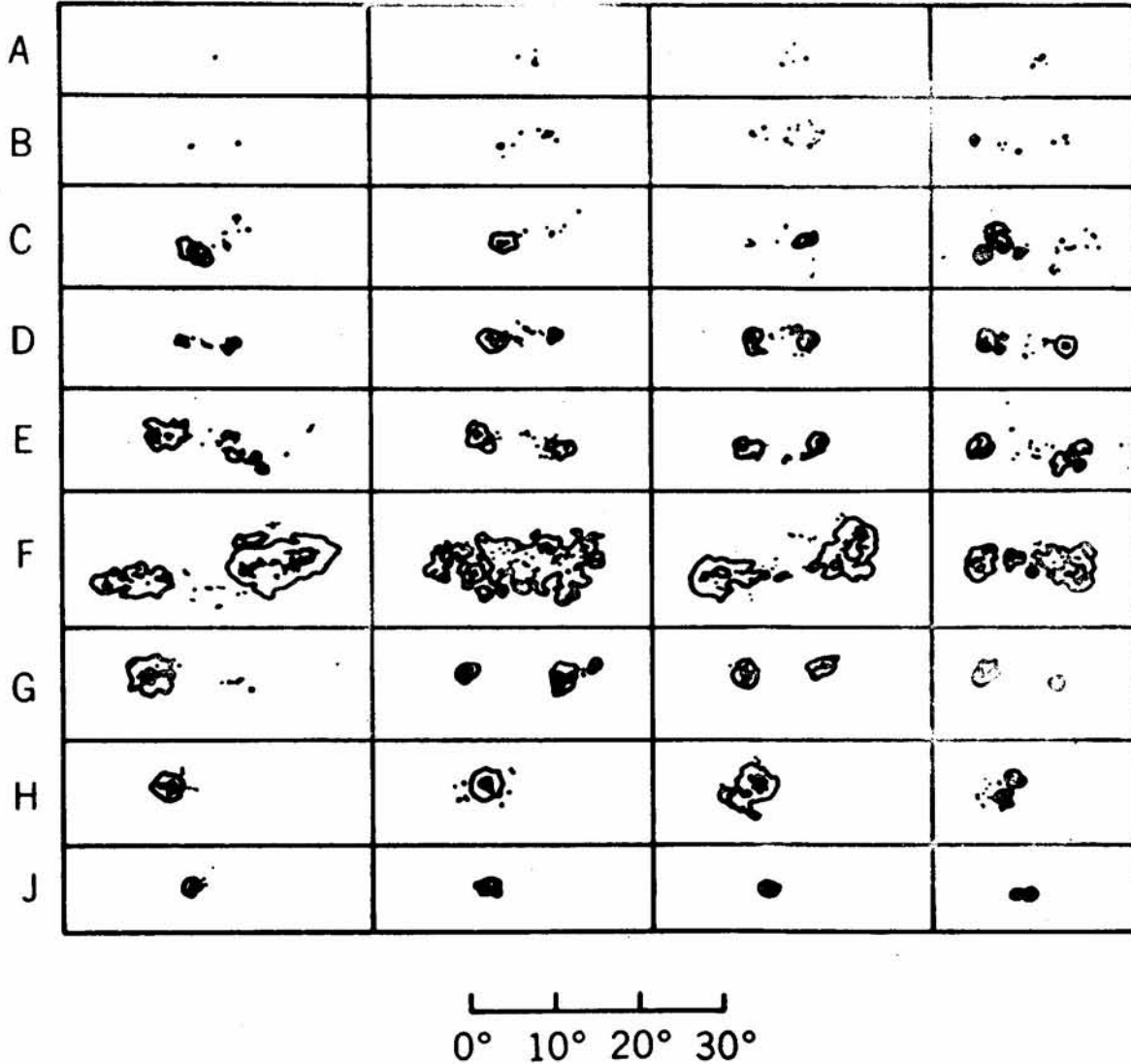


Fig. 31—Relation between flare occurrence and the development of sunspot group¹⁸²

explained by investigating the interaction of shock waves with the interplanetary magnetic field and plasma. Observationally, we have known that the shock waves responsible for type II bursts propagate along the magnetic lines of force in the coronal region^{42,43}. Kopp¹⁸² has tried to theoretically explain this observed result. In case of interplanetary shock waves, it seems necessary to explain the observations, as shown in Fig. 30 on theoretical basis.

It is thought that SSC's occur when those interplanetary disturbances encounter the geomagnetic

field (or the earth's magnetosphere). The cause of the main phase of geomagnetic storms seems to be triggered when flare-ejecta arrive at the earth³². However, we do not know what factor is most important to trigger geomagnetic storms¹¹. It is now known that the main phase of a geomagnetic storm is triggered when the direction of magnetic field transported by flare-ejecta becomes southward. Simultaneously with the start of this phase, auroral flare is broken up. The keV electrons responsible for this flare are supplied from the neutral tail region of the earth's



THE ZURICH CLASSIFICATION OF SUNSPOT GROUPS. FOUR EXAMPLES OF EACH CLASS ARE SHOWN. THE SCALE AT THE BOTTOM INDICATES DEGREE OF HELIOGRAPHIC LONGITUDE.

Fig. 32—Development of sunspot groups (Zürich classifications are given on the sunspot types¹⁸³)

magnetosphere. It seems likely that this flare is characteristically similar to solar flare.

5. Forecasting of Solar Flares

Solar flares are classified into three distinct types: "plage", "prominence" and "sunspot" flares. Among them, the last ones are most important in studying solar terrestrial relations. The occurrence of these flares is highly dependent on the age of associated sunspot groups (Fig. 31). This figure shows that the maximum of the mean daily occurrence frequency of flares is reached when the sunspot group area becomes maximum about 10 days after the birth of sunspot group. At the bottom of this figure, the type of sunspot group proposed by Waldmeier¹⁸³ is indicated. The type of sunspot group is often useful to infer how much sunspot group is active during its growth. Four examples for this classification are shown in Fig. 32. In general, solar flares of great importance are generated in the sunspot groups of type E and F. It is shown that most proton flares occur in these sunspot groups^{184,185}.

These proton flares are always associated with type II and type IV radio bursts. Furthermore, these flares are initiated by the break-up of microwave impulsive and hard X-ray bursts, and the time-profiles of these bursts are very similar to each other (see Fig. 17). Associated X-ray bursts produce SID phenomena on the earth. Recently, Sakurai⁵⁷ has found that the sunspot groups which produce proton flares tend to rotate counterclockwise in the northern and clockwise in the southern hemisphere. This rotating motion produces unusual distribution of magnetic polarities in sunspot group. Thus it seems important to observe the distribution of magnetic fields in sunspot group in order to predict successfully a possibility of proton flare occurrence.

Microwave and soft X-ray observations are also very important in predicting the onset of proton flares^{186,187}. In case of the 7 July 1966 event, Tanaka *et al.*¹⁸⁸ predicted the occurrence of proton flares based on their observation for microwave S-components (3750 and 9400 MHz): when the ratio of 9400 to 3750 MHz fluxes became greater than unity, this occurrence was predicted by them before the onset of the 7 July 1966 proton flare. In order to predict proton flares, therefore, it is important to observe microwave S-component continuously. However, it is difficult to predict the occurrence of minor flares. At present, much effort to find out a method for predicting solar flare onset is being made by studying the characteristics of solar flares and their precursors^{189,190}.

6. Summary and Future Problems

In this paper, we have considered solar flare emissions, both waves and particles and their relation to geophysical disturbed phenomena. In particular, we have reviewed the developmental pattern of solar flares since it seems that the understanding of flare phenomena is most important to find out the cause of geophysical disturbances as described in Section 2. Although many problems have still remained for the study of solar flares, we have known the characteristics of various flare-associated emissions properly responsible for geophysical disturbances. In order to study the flare mechanism, we also need to consider the results deduced from the study of these disturbances. By referring to both solar and terrestrial phenomena, it seems possible to construct a unified view for solar terrestrial relations. This would help us to build up the model of solar flare development, too.

At present, we are too busy in pursuing our own problems, but sometimes we had better think about various fields other than our owns. This would give us some important insight to lead breakthrough for the opening of new fields of science. Although, in this paper, I have been mainly concerned with solar flare emissions, any information for these emissions would be very important to understand the origin of geophysical disturbances. We have not known the true mechanism of "sunspot" flares as yet, but we have a lot of observational results about flare-associated emissions. We believe these results will soon become important for the study of the mechanism of solar flares. Geophysical data would be important for this study.

It is still very difficult to predict the occurrence of solar flares. However, the prediction would be relatively easier if we could find out the true mechanism of solar flares. By observing forerunning phenomena for flares, it would become possible to predict the onset of flares, although, at present, we have not known what these phenomena are.

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