SOLAR FLARE EMISSIONS AND GEOPHYSICAL DISTURBANCES

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Abstract

Various geophysical phenomena are produced by both wave and particle emissions 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 (SID's) are always associated with solar flares, which emit X-rays of wavelength shorter than about 5 Å (e.g., Friedman, 1963, 1964; Neupert, 1969). 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 waves (e.g., Sakurai, 1973a).

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, SSC's are often observed at
the earth. These SSC's are also observed by satellites as the jump of magnetic field intensity, plasma flow speeds and other factors (e.g., Hundhausen, 1970; Chao et al., 1973).

Those geophysical phenomena are all of solar flare origin (Warwick, 1965; Mitra, 1970). 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 (Hα, λ = 6563Å), which gives us an important information for the structure of flares in the chromospheric regions of the sun (Smith and Smith, 1963; Hess, 1964). In addition to this line, several other lines like Hβ, 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, SID's 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 spacecrafts (e.g., Akasofu and Chapman, 1971; Hundhausen, 1972).

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.

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 SSC's 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.

1) SID's

SID's are generated as a result of the sudden increase of the ionization density in the lower region of the ionosphere except for SFD and the increase of the critical frequency foF2. As shown in Fig. 1, for instance, various phenomena
occurred in association with the flare of 16 August 1958 (Hakura, 1958, 1961). In this figure, SEA (Sudden enhancement of atmospherics), 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 SID's.

In addition to the phenomena shown in Fig. 1, it is known that SFD (Sudden frequency deviation), SPA (Sudden phase anomaly), f-min increase and the increase of foF2 are often associated with flares. SID's 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 foF2 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 foF2 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 SID's can give important clue to clarify the spectral distribution of flare-associated emissions responsible for ionizing the ionosphere.

2) PCA

The solar flare of 16 August 1958 was also accompanied by the polar cap absorption, which was detected as the increase of f-min (see Fig. 2) (Obayashi and Hakura, 1960). 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 particles (Rothwell and McIlwain, 1959). These solar particles were emitted from the flare described in this figure, which occurred at 0432 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 polar cap absorption 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 (e.g., Obayashi and Hakura, 1960; Webber, 1962; Reid and Leinbach, 1959; Hultquist, 1959, 1965).
Because of this ionization, the commercial and standard VLF radio waves of the polar routes is affected in a way similar to SEA and SPA as described in subsection 1) (see Egeland et al., 1961; Hakura et al., 1972). 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 equipped the 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 sudden cosmic noise absorptions (SCNA) for the riometer absorption records (e.g., Reid and Leinbach, 1959; Leinbach, 1962; Reid, 1964, 1970). Leinbach (1962) 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 classified to several types; they are currently called F, F*, S and mixed types, as shown in Fig. 3 (Obayashi, 1964).
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 authors (e.g., Hakura, 1967a,b; Sakurai, 1965a, 1971a; Leinbach, 1962; Obayashi, 1962). 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 (Hakura, 1967a,b; Sakurai, 1971a). Hakura (1967a) indicates that, in a typical event, there exist 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 (e.g., Obayashi and Hakura, 1960;

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 (Storm sudden commencement). A typical example is shown in Fig. 4. In this figure, the three components of the geomagnetic field are described; they are the horizontal, vertical intensities and the declination. 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 reached 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 storm (e.g., Obayashi, 1967). This suggests that it is most important to know the mechanism of
geomagnetic storm, because we may find out the physical relationships of this storm with the Forbush decrease, auroral and other phenomena if 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 (e.g., Burlaga and Ogilvie, 1969; Chao and Lepping, 1972). 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 (e.g., Ness and Taylor, 1969; Lazarus and Binsack, 1969). These waves seem to have been sometimes produced as blast waves in solar flares. As shown by Chao et al. (1973), 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 been 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 SSC's 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 (e.g., Akasofu and Yoshida, 1967; Sakurai, 1973b). 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 degrees west of the 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 degrees west of the central meridian plane of the solar disk (Sakurai, 1973b). 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 (e.g., Ness and Taylor, 1969; Bavassano et al., 1970; Lepping and Chao, 1972); 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 ob-
served as the moving source of type II radio bursts tend
to propagate along the magnetic fields near and above the
flare region (Smerd and Dulk, 1971; Dulk, Altschuler and

While propagating through interplanetary space, these
disturbances may deform the configuration of the inter-
planetary magnetic field between the sun and the earth.
This variation of the field seems to be examined by
analyzing the field strength and direction in the region
behind the propagating front of these disturbances (Schatten
and Schatten, 1972). Furthermore, this variation would
affect the Forbush decrease of galactic cosmic rays during
dgeomagnetic storms. Sinno (1962) found that this decrease
is highly dependent on the longitudinal position of parent
flares on the solar disk. As shown in Fig. 6, the per-
centage of this decrease tends to increase as the flare
position moves eastward over the solar disk (Sakurai, 1965a,
1973b). 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 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; the one 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.

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 which some areas on the solar disk suddenly become brighter with respect to the hydrogen Balmer alpha line intensity in the relative meaning. 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 flares (Tandberg-Hanssen, 1973). Sunspot flares are most important for the generation of various wave and particle emissions which produce geophysical disturbances. In general, spectral lines like the Hα 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 Hα emission, for example, relatively increases in comparison
with that for the quiet condition. At first, this increase rapidly goes on and then the Hα 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 Hα brightness is shown in Fig. 8. While the brightness is rapidly increasing, the area of the Hα 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 Hα brightening tends to occur along or across the magnetic lines of force rooted from the sunspot group. By studying the relation between sunspots and Hα brightening areas, Kiepenheuer (1964) has obtained the result as shown in Fig. 10. This figure indicates that the formation of these Hα brightening areas is strongly controlled by the locations of sunspots. Since the generation of sunspots is closely related to the behavior of magnetic fields in the solar photosphere, the location of the Hα 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 Hα 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 (e.g., Severny, 1964, 1969; Sturrock, 1968). 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 (e.g., Parker, 1963; Sweet, 1964, 1969; Priest, 1972a,b; Tandberg-Hanssen, 1973; Sakurai, 1973a). At present, it is known that the sunspot groups of δ-type are very active in producing solar flares (Sawyer, 1966; Sakurai, 1967a, 1970a). These sunspot groups generally show unusual magnetic configuration such that north and south polarity regions appear together in the same main penumbral
regions (Kunzel, 1960; Sawyer, 1966; Sakurai, 1967a, 1972a). Furthermore, the distribution of these two magnetic polarities is unusual for sunspot groups which produce proton flares (Sakurai, 1967a; Sawyer and Smith, 1970; McIntosh, 1970, 1972). The origin of this distribution seems to be related to the rotating motion of sunspot axis (see Sakurai, 1972a). By taking into account the twisting motion produced by this rotating motion, the mechanism of solar flares is investigated (e.g., Sakurai, 1967a; Barnes and Sturrock, 1972). Thus it is very important to study the detailed structure and variation of sunspot groups in reference to magnetic configuration.

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 (e.g., Ellison and Reid, 1964; Sakurai, 1973a). During each phase, several proper emissions are generated as indicated in Table II. 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 emissions (Sakurai, 1973a). 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 flares (see, Stickland, 1969).

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 (1958a,b). 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 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 SWF's, these flares are also associated with X-ray bursts, as expected from the observations of SWF's. In fact, microwave bursts are usually accompanied by X-ray bursts (Fig. 12) (Kundu,
1961; de Jager and Kundu, 1963; Cline, Holt and Hones, 1968). Association of these bursts with type III radio bursts at metric frequencies is well known, as shown in this figure (Anderson and Winckler, 1962; Kundu, 1963; Kane, 1972). Fig. 11 also indicates that the time-profiles of microwave emissions is similar to those for SWF's pattern. This fact suggests that the mechanism of X-ray emissions by flares is closely connected with that of microwave emissions (de Jager and Kundu, 1963; Kundu, 1963; Takakura and Kai, 1966; Takakura, 1967, 1969a). Since it is known that these two emissions are, respectively, generated by bremsstrahlung and gyro-synchroton mechanisms from high energy electrons accelerated in flares, we are able to interpret systematically these emissions by considering the energy spectra and number of these electrons in the flare regions (Takakura and Kai, 1966; Takakura, 1969a, b; Holt and Ramaty, 1969; Holt and Cline, 1968).

In order to understand SID phenomena in greater detail, therefore, we have to know physical mechanism which undergoes in the flare region during each phase as summarized in Table II. As shown in Fig. 11, SWF's always start simultaneously with the start of microwave radio bursts.
Furthermore, the developmental patterns of SWF's are similar to those of microwave bursts at 9400 MHz, for instance (Hakura, 1966).

We shall consider the developmental pattern of a major solar flare and associated wave emissions. This consideration seems to be important for the understanding of the relationships between flare phenomena and geophysical disturbances.

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 II. As shown in Fig. 8, the Hα line brightness rapidly increases for a 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 or flash phases (e.g., Ellison, 1949, 1963). 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 (e.g., Bruzek, 1967; Sweet, 1969; de Jager, 1969; Sakurai, 1973a). A current review on the origin of solar flares is described in Tandberg-Hanssen (1973).

While the Hα 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 of microwave type IV bursts (IVμ) 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 for running 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$_\mu$, IV$_m$, IV$_{SA}$ and IV$_{SB}$. Since the classification of these components is very different from one author to another, the result shown here must be considered as one of these classifications (see, Wild, 1962; Fokker, 1963; Kundu and Smerd, 1962; Takakura and Kai, 1961; Kundu, 1965). As shown in this figure, microwave type IV burst (IV$_\mu$) starts before the emission of microwave burst (M-W) ceases.

Moreton (1960) observed the surface waves propagating away from the flare region, 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 for this wave as shown in Fig. 15 (see, Ramsey and Smith, 1966; Martin and Harvey, 1971). This result shows that this wave propagated into some limited direction within \( \sim 90 \) degrees. 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 don't propagate in every direction from the flare region has not been found yet. Recently, Uchida et al. (1973) 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 (1971b,c), 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 solar X-rays > 80 Kev observed by the IMP-3 satellite is almost the same as the intensity-time profile of microwave burst at 17,000 MHz (Cline et al., 1968). This suggests that the source for these two emissions must be the same (Takakura and Kai, 1966; Takakura, 1969a,b; Holt and Cline, 1968; Holt and Ramaty, 1969). Because it is known that these X-ray emissions (< 1Å) are responsible for the production of SID's, these solar X-rays associated with the flare of 7 July 1966, as shown in Fig. 17, must have produced SID's. Hakura (1969) found that the time variation of SCNA observed at Penticton, Canada, is almost the same as that of soft X-ray burst (< 14Å), which was reported by Van Allen and Ness (1967). The intensity-time profile of this soft component is not fully equal to that shown in Fig. 17, but the starting time of both emissions is 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 plasma (e.g., Friedman, 1964, 1969). These two components have been directly found by using the observation of several channels for energy by the OGO-5 satellite (Fig. 18) (Kane, 1969). The first peak in this figure are 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 (Frost, 1972; Simnett, 1973). This tendency is also seen in microwave radio burst (see, Fig. 17).

Chupp et al. (1973) first observed gamma-ray bursts from the solar flares 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 (Svestka, 1970; Sakurai, 1971b).

The expansion of shock waves from the region where a flare triggered, is a good measure for the start of the main phase of flares (Sakurai, 1966). 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 (Smerd and Dulk, 1971; Sakurai and Chao, 1973a). The sources of type IV radio bursts at metric frequencies (IVm 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\(\mu\) burst does not move out of the flare region, this source seems to be independent of the source for type IV\(\nu\) burst (e.g., Kundu, 1965; Takakura, 1967; Sakurai, 1971d).

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\(m\) 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 (1973c,d) 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 region (Dulk, et al., 1971), 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 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 SSC's 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 (e.g., Kawabata, 1960, 1963). SID phenomena are associated with this X-ray emission. It is interesting to note that there seem to exist two types of this thermalization process as shown in Fig. 20 (Hakura, 1966); 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 (IVS-B) is often identified as type I noise source. The emission mechanism for these two sources seems to be the same (e.g., Kai, 1970); they are generated by some plasma processes related to electron plasma oscillation. Sometimes, stationary loop prominences are formed (Bruzek, 1964a,b). 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 (Jefferies and Orrall, 1965a,b).

These particles are gradually emitted into outer space for the period from several hours to a few days (Simnett and Holt, 1971; Simnett, 1972; Sakurai, 1973e). The duration of this period seems to be related to the magnetic configuration of the flare region. Therefore, the duration of continuum emissions IV_s A and IV_s B is also dependent on this configuration because these emissions are produced by energetic electrons trapped by sunspot magnetic fields.

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 (e.g., Ellison et al., 1971; Sakurai, 1965b, 1971b; Svestka, 1970). The acceleration mechanism has not been fully understood for these particles, but Sakurai (1965c, 1971a) has shown that the Fermi acceleration works efficiently.
to produce high energy particles. General theory of particle acceleration is discussed in several references as follows: Hayakawa et al (1964), Wentzel (1965), Sakurai (1965d,e), Schatzman (1967) and Hayakawa (1970).

The ejection of the main part of these particles into outer space is associated with the expansion of magnetic bottles (Sakurai, 1969b). Therefore, it seems that these particles are emitted into interplanetary space before the end of the explosive phase (Ellison et al., 1961; Mathews et al., 1973). 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 (Hayakawa, 1970; Sakurai, 1973a). 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 references; Carmichael (1962), Ellison (1963, 1964), McCracken (1962, 1969), McCracken and Rao (1970) and Sakurai (1973a).
Mev solar cosmic ray events were discovered by Bailey (1957, 1959) 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 (e.g., Bailey, 1957; Webber, 1962; Reid, 1963, 1967). 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 cycle, as shown in Fig. 21 (Collins et al., 1961; Svestka and Olmr, 1966; Sakurai, 1967b). It seems likely that Bev events do not occur during the maximum phase of this cycle (Takakura and Ono, 1961, 1962).

Hakura and Goh (1959) 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 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 events (Sakurai, 1963). The importance of A type spectra for the generation of solar cosmic rays has been pointed out by Castelli et al. (1967, 1968), who called them the U-shape spectra.

Analyzing the IMP-3 satellite data, Cline and McDonald (1968) 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 et al. (1962)
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 Boischot and Denisse (1957), but, for many years, no direct evidence had not been obtained. As Sakurai (1972b) 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 there (Hakura, 1967a).

Van Allen and Krimigis (1965) first reported that solar flares of minor importance produced > 45 Kev electrons. Since the most these flares do not produce distinguished
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 (e.g., Lin, 1970; Lin and Anderson, 1967; Kane, 1972). 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 (Hirshberg et al., 1972; Hirshberg, 1973). Since the thickness of these shells observed at the earth's orbit is dependent on the longitudinal position of parent flares (Fig. 24), the expansion of these shells also seems to occur anisotropically in the space between the sun and the earth (Sakurai et al., 1973b). 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 interplanetary disturbances generated by flares.

3) Flare development related to the emissions described in 1) and 2).

So far we have considered both wave and particle emissions by using observed results. As shown in 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 summarize these associations in Table III 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 SID's
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 in Table IV (Takakura, 1967; Bruzek, 1967). 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, respectively. When we consider the total amount of flare-energy released in a major flare to be several times of $10^{32}$ ergs (e.g., Bruzek, 1967, 1969; Sakurai, 1973a), 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 (see, Sweet, 1969; de Jager, 1969; Sakurai, 1973a).

It seems better to summarize the relationship between flare-associated emissions and geophysical phenomena (Table
V). 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 V, it is known what type of solar emissions produces proper disturbances at the earth; wave emissions are mainly responsible for SID phenomena, whereas particle 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.

1) SID's

Fig. 20 shows that there exist two distinct patterns for SWF's. The time-profile of these SWF's 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 (e.g., Kawabata, 1960; Hakura, 1966). Therefore, these SWF's are explained by considering these X-ray emissions from flares.
The developmental pattern of SEA's is dependent on the characteristics of solar flares. When we use several frequencies to observe SEA's, we are able to find out such dependence (Sakurai, 1968, 1969c). Two examples are shown in Fig. 25, which are associated with proton flares. The SEA's 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 behavior of 10 kHz field intensity is also significantly different between them. By studying these characteristics of SEA's, therefore, we can estimate what is going on the sun. Since the duration of these rise times is correlated with that of the Hα brightness increases, it is clear that the fastness of the thermalization of the flare plasmas plays a main role for the X-ray emission from the flare region (Sakurai, 1970b). It has been statistically shown that the rise time of solar X-ray emission is proportional to that of the Hα brightness (Thomas and Teske, 1970). These results suggest that SID phenomena are completely dependent on the developmental pattern of flare X-ray emissions.
The developmental pattern of SCNA's is almost the same as that of SWF's, 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 called "sfe" (e.g., Akasofu and Chapman, 1971).

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 regions (Kanellakos et al., 1962a,b; Donnelly, 1966, 1967). The ionization of this part is produced by the EUV emissions from flares. The satellite observation of the He II 304Å resonance line intensity, for instance, shows that this intensity rapidly increases with the onset of the explosive phase of flares (Neupert, 1964). The continuum EUV emissions
show a similar increase as does the He II 304Å intensity (Donnelly, 1968).

When Knecht and McDuffie (1962) 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 SID's are all generated by the enhanced ionization of the earth's upper atmosphere by solar X-ray and EUV emissions associated with solar flares.

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 (e.g., Störmer, 1955; Gall et al., 1968). As Schlüter (1958) 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 field (see, Alfvén, 1950; Northrop, 1963; Sakurai, 1961). The result for these orbital motions shows that these particles can only approach the polar latitude regions, although depending on their rigidities.

Obayashi and Hakura (1960) studied the developmental pattern of the polar cap absorption (PCA) 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 degrees N and S, but this latitude is lowered down to ~65 degrees when the main phase of geomagnetic storms starts. This variation is related to the geomagnetic variation during storms. Hakura (1967a) 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 degrees 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 space (Sakurai, 1965a); that is, this cause is made clear when we consider the duration from forgoing 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 (e.g., Reid, 1963, 1966, 1970; Reid and Sauer, 1967; Dessler, 1964; Michel and
Dessler, 1965; Hakura, 1967b; Gall et al., 1968). 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.

3) Flare-generated interplanetary disturbances

About 90 percent of solar flares associated with both type II and type IV radio bursts are followed by SSC geomagnetic storms (Chao, 1973, private communication). 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 (e.g., Stewart et al., 1970; Dulk, 1971; Dulk et al., 1971). 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 space (Chao, et al., 1973). 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 satellites (Sakurai, 1973f).

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 corona (Sakurai and Chao, 1973a). 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 (see, Pinter, 1973; Sakurai
and Chao, 1973a).

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. Sakurai
(1973f) has analyzed a series of flare-generated inter-
planetary 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 degrees west of the central meridian of the solar
disk. Using this result, the mean propagation pattern of
the interplanetary disturbance at 1 AU 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 waves (Sakurai and Chao, 1973a).

Anisotropic propagation of interplanetary disturbances has been first suggested by Ness and Taylor (1969) 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 (e.g., Bavassano et al., 1970; Lepping et al., 1972). Although it is very difficult to theoretically explain such anisotropic propagation pattern as shown in Fig. 30, these observations must be 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 (Dulk et al., 1971; Wild and Smerd, 1972). Kopp (1972) 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 earth (e.g., Obayashi, 1967). However, we do not know what factor is most important to trigger geomagnetic storms (see, Akasofu and Chapman, 1971). 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. Kev electrons responsible for this flare are supplied from the neutral tail region of the earth's 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 Waldmeier (1957) 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 (Anderson, 1961, 1964).

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, Sakurai (1967a) has found that the sunspot groups which produce proton flares tend to rotate counterclockwise (clockwise) in the northern (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 (Tanaka and Kakinuma, 1964; Friedman and Kreplin, 1969). In case of the 7 July 1966 event, Tanaka et al. (1969) 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 method for predicting solar flare onset is being made by studying the characteristics of solar flares and their precursors (see, Simon, 1969; McIntosh and Simon, 1972).
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 become soon 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 forrunning 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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Table I  Flare-associated emissions and related geophysical phenomena

<table>
<thead>
<tr>
<th>Flare-associated emissions</th>
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<tbody>
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<td>SWF</td>
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<td></td>
<td>SEA</td>
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<td></td>
<td>SCNA</td>
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<td></td>
<td>sfe</td>
</tr>
<tr>
<td>EUV burst</td>
<td>SFD</td>
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<tr>
<td></td>
<td>ΔfoF2 increase</td>
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<tr>
<td>Solar cosmic rays</td>
<td>PCA</td>
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<tr>
<td>(Mev-energy)</td>
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<td>Flare-ejecta</td>
<td>Geomagnetic storm</td>
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## Table IV Flare energy and flare-associated particles

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Table V  Geophysical phenomena produced by solar flares

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<td>EUV (including He II 304\ang)</td>
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<td></td>
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<tr>
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<td>SFD</td>
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<td>ΔfoF2 increase</td>
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<tr>
<td></td>
<td>PCA</td>
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<tr>
<td></td>
<td>Geomagnetic storm</td>
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Table III  Particles accelerated in solar flares and related solar and geophysical phenomena

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<td>Microwave bursts</td>
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<td>Type IV bursts</td>
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<td></td>
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<td></td>
<td>White light emissions</td>
<td></td>
</tr>
<tr>
<td>Heated flare plasmas</td>
<td>Thermal X-rays</td>
<td>SID</td>
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<td></td>
<td>Microwave bursts</td>
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Table II  Developmental pattern of solar flares and associated emissions

Preflare state

- $H\alpha$ 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

Explosive phase

- Sudden expansion of the $H\alpha$ bright area
- Sharp increase of $H\alpha$ 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)

Main Phase

- 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

Late Phase

- Stationary continuum storm
- Flare nimbus
- Loop prominence system
Caption of Figures

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 shown (Hakura, 1961).

Fig. 2 Polar cap absorption produced by the invasion of solar cosmic rays as observed at Alert, Canada (Obayashi and Hakura, 1960).

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, H,D,Z are indicated.

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.

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

Fig. 8 The time-profile of the Hα line brightness.

Fig. 9 The Hα brightening area for a fully developed flares. This area covers the most part of sunspot umbral regions.

Fig. 10 Relation between sunspots and the Hα brightening areas (Kiepenheuer, 1964).
Fig. 11  Three types of the development of solar radio bursts and SWF's associated with solar flares. 1) SWF type, 2) geomagnetic storm type and 3) solar proton type. (Hakura, 1961)

Fig. 12  The time profiles of both microwave and X-ray bursts and associated type III radio bursts (Anderson and Winckler, 1962).

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.

Fig. 15  Picture of the Moreton wave associated with the solar flare of 20 September 1963 (Martin and Harvey, 1971). White part is the Hα 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.

Fig. 17  The intensity-time profiles of microwave and hard X-ray bursts associated with the flare of 7 July 1966 (Cline et al., 1968).

Fig. 18  The developmental patterns of X-ray bursts as observed by different energy channels (Kane, 1969).

Fig. 19  Motion of magnetic bottle and forerunning shock wave above the flare region (Sakurai, 1973d). Trapped electrons are identified as the source of metric type IV burst ($\text{IV}_M$).
Fig. 20  Two distinct developmental patterns of SWF's. They are very similar to those for microwave radio bursts (Hakura, 1966).

Fig. 21  Long-term variation of the occurrence number of solar proton flares, Bev and Mev, for the solar cycle No. 19 (Sakurai, 1967b).

Fig. 22  Two representative peak flux spectra of type IV radio bursts. The spectra A are associated with flares which produce F and F* types of solar proton events, whereas the spectra B are related to those for S type events (Sakurai, 1969b).

Fig. 23  Satellite observation of Mev electrons associated with the solar flare of 7 July 1966. Proton data are also shown. (Cline and McDonald, 1968).

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

Fig. 25  Two distinct patterns of SEA's associated with solar proton flares (Sakurai, 1968). (a) SEA associated with Bev proton flare, (b) SEA associated with Mev proton flare.

Fig. 26  Schematic representation of three phases of the development of polar cape 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 events as shown in Fig. 3 (Sakurai, 1965a).
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 other (Sakurai and Chao, 1973a).

Fig. 29  Time intervals from solar flares and SSC geomagnetic storms during 23 October to 4 November 1968. These flares occurred in the active region McMath No. 9740 (Sakurai, 1973f).

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 group (Waldmeier, 1957).

Fig. 32  Development of sunspot groups. Zürich classifications are given on the sunspot types (Waldmeier, 1957).
FLARE (3+)

RADIO BURST (200 MHz)
HIRAISO

GEOMAGNETIC FIELD
H–COMPONENT (sfe)

SEA (28 KHz)

SWF (20MHz)

SCNA (50 MHz)

04 05 06 07

UT

16 AUGUST 1958

Fig. 1
SOLAR-TERRESTRIAL EVENTS ON AUGUST 16-18, 1958.

Fig. 2
RANGE H 280 γ
Z 80 γ

9 AUGUST 1972
SSC 0036 U.T. KAKIOKA, JAPAN

fig. 4
Fig. 5
Fig. 7

- FLARE REGION

- SHOCK FRONT SHAPE

- SUN

- LOW

- HIGH

- INTENSITY OF MAGNETIC FIELDS

- A.U.

- EARTH
Fig. 8

McMATH HULBERT OBS.

NOV. 12, 1960

Fig. 9
Fig. 11
Fig. 12

TYPE III BURSTS

9500 MHz $\nu_{\mu}$
(Tokyo)

X RAYS

INTENSITY

UT 28 SEPTEMBER, 1961
Fig. 13

SEPTEMBER, 1963 (U.T.)
DIRECTION OF THE MORETON WAVE PROPAGATION

SOLAR FLARE IMP. 2B
2347 UT 20 SEPTEMBER, 1963
N10° W09°

Fig. 16
JULY 7, 1966

MICROWAVES
17,000 MHz

SOLAR X-RAYS
> 80 KeV

PHOTONS · CM⁻² · SEC⁻¹

WATTS · M⁻² · HZ⁻¹

0020  0030  0040  0050

U.T.

Fig. 17
Fig. 18

F (10568)
(N20, E05)

SIMPLE 2
8800 MHz

Hα – FLARES

RADIO BURSTS

SOLAR X-RAYS
OGO-5
9.6–19.2 KEV (rate x 1.0)
19.2–32 KEV (rate x 1.0)
32–48 KEV (rate x 0.2)
48–80 KEV (rate x 0.02)

RATE (counts/sec)

10^4
10^3
10^2
10
10^{-1}

10 FEB. 1970
EXPANDING SHOCK WAVE

ENERGETIC ELECTRON CLOUD

SUNSPOT GROUP

WEST

EAST

♦ FLARE SITE

VIEWED FROM NORTH

Fig. 19
Fig. 20
UNUSUAL INCREASE

SMALL INCREASE

(\Delta I/I \leq 5\%)

Fig. 21
Fig. 24
Fig. 25
Fig. 26

- Electrons
- Protons
- α-particles
TIME INTERVAL FROM SC TO PCA ONSET (days)

TYPES OF SOLAR COSMIC RAY EVENTS

Fig. 27
A: SHOCK WAVE EXCITING TYPE II BURSTS
B: MAGNETIC BOTTLE (SOURCE OF TYPE IV BURSTS)

$V_I$: SPEED OF TYPE II ASSOCIATED SHOCK
$V_B$: SPEED OF MAGNETIC BOTTLE
$V_I$: SHOCK SPEED IN INTERPLANETARY SPACE

INTERPLANETARY SHOCK WAVE (6 NOV. 1968)

$V_I \approx 650$ KM SEC$^{-1}$

Fig. 28
PERIOD: OCTOBER 23 – NOVEMBER 4, 1968

TIME INTERVAL BETWEEN FLARE AND SSC

(HOURS)

0 30° 60° 90° 120° 150° 180° 210° 240° 270° 300°
EAST

0 30° 60° 90° 120° 150° 180° 210° 240° 270° 300°
WEST

SOLAR LONGITUDE

Fig. 29
PROPAGATION PATTERN OF FLARE-ASSOCIATED INTERPLANETARY DISTURBANCES NEAR THE EARTH

<: FLARE POSITION

VIEWED FROM NORTH

Fig. 30
Fig. 31

Spot Group Mean Daily Flare Number

Spot Group Area

Type of Spot Group

Days from Birth of Spot Group

Fig. 31
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

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