Chapter II

Acceleration and transport of solar cosmic rays

Impulsive and Gradual Flares

From physical, X-ray emission features, solar flares have been divided into 3 groups (Pallavicini, Serio, & Valana 1977) which are A: the loop flares, B: the point flares, and C: the big flares that have diffusion in the loop. Physically, we can measure variables such as the height, volume, temperature (10^7K), density, duration, and other physical features. All these variables allow us to divide flares into 2 classes. Class 1 is for flares of classes A and B. Flares in this class are of low volume, lower height, short duration (fast increase and fast decay), are not related to white-light coronal transients, have high energy density, and sometimes the flares in this class are called "impulsive events." The other special features are that it will happen in the lower corona, with type III and V radio bursts that generate electrons and ^{3}He and energy emitting from the corona downward. Class 2 is for flares of class C that have a long duration, larger volume, lower energy density, are related to white-coronal transients, and sometimes the flares in this class are called "gradual events." It will happen in the higher corona, have type II and IV radio bursts, more ^{4}He, and are related to explosions or stimulation. Energy emission is upward. Conclusion are summarized in the table below:

Impulsive flares	Gradual flares
1. emit x-rays in short time scale ($<$1hr)	emit x-rays in long time scale ($>$1hr)
2. emit x-rays from low position ($\leq 10^4$ km from photosphere)	emit x-rays from high position ($\approx 5\text{x}10^4$ km from photosphere)
3. emit x-rays from a compact region (10^{26}-10^{27} cm^3)	emit x-rays from a wide region in magnetic loop (10^{28}-10^{29} cm^3)
4. high energy density	low energy density
5. downward energy emission from corona	upward energy emission from corona
6. may have Type III or V radio bursts (III: plasma oscillations from relative electrons)	may have Type II or IV radio bursts (II: plasma oscillations from slower electrons, IV: gyrosyn chrotron radio waves from electrons)
7. may have γ-ray line emission	might not have γ-ray line emission
8. low flux of particles	may have a high flux of particles
9. high e/p ($\approx$0.1-1)	low e/p
10. very high ^{3}He/^{4}He ($\approx$0.1-1)	normal ^{3}He/^{4}He ($\approx 10^{-4}$)
11. high Fe/O	low Fe/O
12. high average of Si, Fe ions	low average of Si, Fe ions
13. acceleration from high temperature plasma (10^7 K)	acceleration from normal temperature plasma (10^6 K)
14. will not have coronal mass injection, interplanetary shock	will have coronal mass injection, interplanetary shock

Table 2.1: Summary of the impulsive and gradual flares.

Acceleration Ideas

Cosmic rays from the Sun have been studied for a long time. Two main acceleration mechanisms are now believed to account for these particles. One idea is acceleration by coronal or interplanetary shocks (Lee and Ryan 1986). Energetic particles escape into interplanetary space after they are accelerated at a coronal or interplanetary shock created by the flare. The flare starts suddenly in an unstable magnetic field. When the magnetic field slows down and decays and then connects again, this results in accelerated electrons and 10-100 keV ions, and accelerated plasma. Those electrons emitted follow the open magnetic field line.

Temperature rapidly increases and mass is emitted, and a shock is generated, and propagated throughout the thick corona with velocity of (1-2)$\times 10^3$ km/s. Furthermore. shock accelerated energetic particles arise in the impulsive phase by a first-order Fermi mechanism. The second idea is that the first-order Fermi acceleration process is not enough, because of work done in the foreshock region of the shock, and if this shock weakens, this process will not affect particle acceleration. If acceleration by the shock affected many ions, substantial backstreaming ion fluxes would be observed in the same direction with other particles. The second-order Fermi acceleration process is very important in the far upstream region so shock acceleration works close to the bow shock. Especially while the shock is strong enough, it could extract electrons and ions from shock-processed plasma and accelerate electrons up to 1 MeV and ions up to 1 GeV per nucleon. Finally the shock passed through open field lines. Then abundant accelerated particles were ejected from confining turbulence to interplanetary space.

In the second-order Fermi acceleration process, ions are accelerated by the component of transverse wave current. If the wave component exists in turbulence, particles will be accelerated by stochastic mirror forces exerted by these waves. However, when the energy density of transverse waves is large compared to magnetosonic waves, acceleration by transverse waves dominates. The stochastic acceleration effect from magnetosonic waves will be important if transverse waves are very weak compared to nondirectional magnetosonic waves or transverse waves. The other acceleration process from magnetosonic waves is the shock-drift mechanism working at the wave edges. This mechanism will be very effective when the distribution angle, θ_{kB}, the angle between the wave vector $\vec{k}$ and background magnetic field $\vec{B}$, must be close to 90^o. It does not accord to this situation if θ_{kB} is less than 30°.

Acceleration Time Scales

The impulsive flares and gradual flares have their origins in different regions in the corona. If the energy emission takes place low in corona where the energy density is high, the emission takes place rapidly and the observed phenomena occur on short time scales (Cane, McGuire, & von Rosenvinge 1986). The particles observed in space are proton-poor. Energy emission will lead to the expulsion of material in the upper corona and it will travel out into the planetary medium generating a shock in front of it. The slower time scale of this type of event is more favorable for the acceleration of protons.

Coronal Diffusion

Both gradual and impulsive events are found to have different signatures, not only in their source properties but also in the abundance of the particles observed in interplanetary space. Class I or impulsive events have short-duration (<1 hr) X-ray profiles arising from intense regions relatively low in the corona. Energy for particle acceleration in these events probably comes from the magnetic field line reconnection in areas of newly emerging flux. These events comprised of type III and type V radio bursts that generated by electrons. These impulsive events also generate γ-ray too. Class II or gradual events have long-duration (>1 hr) X-ray profiles arising from the extended regions high in the corona. These gradual events produce coronal mass ejections, generate coronal and interplanetary shocks, and exhibit type II and type IV radio bursts. The X-ray profiles probably comes from the magnetic field line reconnection relatively high in the corona after the extensive disruption of the coronal fields by the injected particles. These events corelate with kilometric type III radio bursts which are excited by solar electrons streaming outward through interplanetary space but found less corelation with phenomena deeper in the solar atmosphere (Reames & Stone

1986). Furthermore, radio emission may be a sensitive indicator of event classes and mechanisms than the soft X-ray profiles.

Acceleration by Coronal Shocks

In the first phase the associated radio bursts are called type III, and the responsible particles are electrons with energies in the range 10-100 keV. The groups of type III bursts and the hard X-ray bursts has been interpreted as indicating the population of electrons that is responsible for all classes of emission. The second phase of energetic solar flares is normally observed type II burst which is indicative of a shock. The more intense bursts are accompanied by type IV emission, but occasionally the type IV occurs alone.

The word "phases" of particle acceleration in solar flares was used because it was believed that the second could not occur without the first. The observations of energetic particle events with "weak impulsive phases" and other events with no signature at the Sun except for an eruptive prominence. The formation of coronal and interplanetary shocks may occur even without observation of an impulsive energy release or particle acceleration. The impulsive flares can lead to particle events with well-defined characteristics (Cane, McGuire, & von Rosenvinge 1986). In generally, only flares which are well connected and there are open field lines from relatively low in the corona produce energetic particles in the interplanetary medium. The observation of the type III bursts with the detected impulsive particle events verifies that there are open field lines. The fact that the source region needs to be well connected implies that the particles are released in the specific region and are accelerated by coronal shock.

A type III burst is the signature of an impulsive acceleration at the Sun. The emission comes from a stream of electrons which is not usually accompanied by the fluxes of protons. These electron events are electron-rich or proton-poor.

In intense impulsive flares the type III electron stream extends to relativistic energies. The reported correlation of electron-richness with the production of γ-rays. These impulsive events, relativistic electrons were generated. In general low-energy electrons are present at the Sun for both classes of flares because of the associated with hard X-ray emissions, but in the long-duration events these electrons apparently do not escape to the interplanetary medium. A very intense impulsive event can produce an interplanetary shock and a long-duration event can be associated with a very energetic impulsive acceleration. In the most impulsive flares the protons are accelerated impulsively but that in events which energies extend to above 40 MeV and associated with coronal mass, a substantial fraction of protons are accelerated at the coronal shock. The impulsive events are proton-poor. In a few cases the ratio of electron to proton at an energy near 3 MeV was found to be greater than unity. The impulsive flares rarely produce interplanetary shocks, thus the events are the short duration. Since the verifying feature of the intense type III bursts, the electrons comprise a high energy of the type III radio emission. The energetic particles in the impulsive flares are accelerated by the so-called first-phase mechanism.

The high energy proton events are associated with long-duration soft X-ray events, and produce the strong interplanetary shocks, and there are more protons than electrons. In long-duration events, second-phase or coronal shock acceleration plays the dominant role. Many of the events show that no evidence of the escape of the particles from the first phase (there are no type III bursts preceding the type II bursts). Some events have only weak impulsive acceleration.

The fact that impulsive flares occur low in the corona, compact, and have the high energy densities, but the long-duration flares occur high in the corona in extended regions.

Interplanetary Transport

Solar energetic particles are evidence of release process in the solar active regions. An energy which stored in the magnetic field, is transferred to particles that can be raised up to hundreds of MeV, and some is converted into shock waves, traveling through the corona and the interplanetary medium (Kallenrode 1993). These solar energetic particles can be observed on interplanetary magnetic field lines connecting back to a point in the corona far away from the flare site. For a long time it has been concluded that this is due to azimuthal transport taking place at the level of the solar corona, but not in the interplanetary medium. An explanation for the azimuthal transport is diffusion perpendicular to the magnetic field at larger radial distances in the interaction regions. However, those events are easily identified because the particles would come from the antisolar direction.

In impulsive events the particles are accelerated in the low corona and escape along open field lines, in gradual events the particles are accelerated by a shock. This may be a coronal shock (large-scale shock acceleration), an interplanetary shock, or a combination of both. In these events there are no (or negligible) azimuthal transport of particles accelerated in the flare site but the acceleration is specially extended. Limitations to most of the models, propagation as well as specially extended acceleration, are given by the two regions of propagation: A "fast propagation region" extending azimuthal up to $50^o - 60^o$ around the flare site, in which protons may be transported very fast within 1 hour up to angular distances of about 50^o. The outside temporal delay increases considerably with increasing azimuthal distance. There is no abrupt cessation of particle transport outside, rather a drop in efficiency of the transport. Its extension varies with the solar magnetic field topology and can be as small as 25^o.

For individual events the azimuthal propagation is controlled by the large-scale photospheric field, abrupt changes in the particle intensity profiles of low energy protons (0.3 to 12 MeV) correspond to times when the footpoint of the observer's magnetic field line crosses a neutral line of the photospheric magnetic field.

Not only neutral lines extending into the interplanetary medium (that are the neutral lines of the high coronal field on the source surface forming the sector boundaries in interplanetary space), but also the neutral lines of the chromospheric field forming the small-scale polarity patterns of active regions can cause abrupt changes in particle fluxes. The main mechanism for the particle escape is a drift along the neutral line. Electrons have fast escape and accessed to a slow solar wind stream directly surrounding the active region, but that no electrons are injected in an adjacent fast stream. The ^{3}He-rich events were only discovered in slow solar wind streams.

The important role of the large-scale coronal magnetic field for the azimuthal transport of energetic particles may be a real transport (Kallenrode 1993) or the extended particle acceleration at an interplanetary/coronal shock. The variable extension of the fast propagation region is supported by the relatively large angular distances from the flare the azimuthal propagation between the two spacecraft can be fast if both spacecraft are connected to the flare sector and can be slow at smaller distances.

The acceleration on open field lines by a shock as the only process for release of particles remote from the flare site is difficult to compare with the time scales of propagation and the different propagation speeds of electrons and protons. In addition, the role of a type-II shock for the acceleration of energetic particles is not clear, thus the coronal mass ejection/interplanetary shock are more important, because it is clearly established. In case of impulsive flares (which have no interplanetary shock) neutral lines to be the boundaries of the open cone and propagate the particles to the magnetic field sector adjacent to the flare sector. The explanation by separating coronal propagation mechanism is very difficult at the two different time-scales of propagation with requires two different mechanisms.

Effect of Interplanetary Shocks Near/Far from Earth

The interplanetary shocks play a significant role in particle acceleration in large event, even at relatively high energies. The most intense events come from flares near central meridian, as do the strongest shocks, rather than from a longitude of 50°-60° W when the Earth has the best magnetic connection to the flare. For particles above 1 MeV, the effects of the shock were usually nonlocal, the intensities occur when the observer's magnetic field line is connected to the region of the shock and not when a weaker portion of the shock passes the spacecraft. The Fe-rich (Fe/O ≈1.0) events have been associated with impulsive flares from which highly ionized hot material is ejected while the Fe-poor (Fe/O≈0.1) material is accelerated by a shock from the cooler ambient gas in the corona or the solar wind.

For several years there has been increasing evident for the energetic particles in association with solar flares. The profile and the abundance seen in the large events. Many of the large events are dominated by acceleration of material from the solar wind by the interplanetary shock. These shocks cross magnetic field lines to accelerate particles in regions that are not connected to the flares.

The particles are accelerated as they are trapped near a shock (Lee 1983). The high particle intensities can cause the a high growth rate for waves near the shock, and an equilibrium is established where the intensities depend only upon distance from the shock. Upstream of the shock, the intensities of the particles decline and the growth time scale of the waves becomes sufficiently long that the particles begin to stream freely away. Evidently, this point is reached at an intensity corresponding to 100 protons (cm^2 sr s MeV)$^{-1}$ near Earth (Reames 1989).

High-energy particles, as well as low-energy particles, are also accelerated by the interplanetary shock in large proton events. The intensities of high-energy particles often peak when the coronal mass ejections and the interplanetary shocks that they drive have reached distances of 8-10 solar radii, well above the solar corona. Observations of the angular distributions of particles near shocks at 1 AU show particles streaming away from the shock in both the upstream and downstream regions (Reames 1990).