Relationship between Solar Flares and Solar Cosmic Rays

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Abstract: We discuss the possibility that the plasma trapped inside the solar magnetic loop region may be the principal arbitrator in deciding whether a given active region will release particles into the interplanetary medium or will remain a solely electromagnetic event. We analyze the particle abundance patterns and show that the particle selection occurs in a cool region much below the corona. We discuss the particle acceleration in time varying magnetic field and show that the betatron process can be very effective under solar conditions. We then show that the electron density in the flare region may be the critical parameter in deciding the evolution of the active region. Finally we show that direct observations of flares in the interplanetary medium agrees well with this suggestion.

Introduction: It has been generally suggested that magnetic flux tubes form at the bottom of the convection zone, and at some stage become unstable and rise to the surface under magnetic buoyancy to give magnetic activity on the outer atmospheric layers of the Sun (cf Wilson, 1986). Once this upward motion has begun, it is generally assumed (Piddington, 1975) that the dynamo action ceases and the plasma within the tube remains isolated (Wilson, 1986). Above the photosphere, these loops build up in strength and become bright in Hα (cf Priest, 1981).

In the case of large flares, electromagnetic loops rise high into the upper corona of the Sun and then give particles from large open loop regions. In some cases, the flare loops may simply brighten in the electromagnetic band, giving rise to a large variety of radio and X-ray emission without any accompanying particle emission. Recent satellite measurements have also identified a class of events where small electromagnetic activity as well as particle emission occurs. Under such a condition, the particle abundances tend to be invariably peculiar. Since all this activity is, at its source magnetic, we investigate the possibility that the particles trapped in solar flare loops may mediate in the evolution of the all this activity. We show that for reasonable values of the parameters like the time scales and intensity of magnetic field variations in the flare region, the plasma trapped inside the magnetic loops can efficiently convert magnetic energy into electromagnetic energy then show that the physical conditions of the plasma trapped inside a magnetic loop may decide whether a given active region will remain purely electromagnetic event, or a small or large particle release event. We finally show that the above suggestion is well borne out by comparing the suggest made here with those made from direct observations of various of various types of flares.

Basic Selection and Acceleration process: Several studies of the large flares have established a common abundance pattern for solar cosmic rays (cf Biswas et al, 1983; Mason et al, 1986; Vahia et al, 1988) in large flares. In the literature the classification of elements is made according to their first

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ionisation potential (cf Biswas et al, 1983, Meyer, 1985). However, this classification is, at best, only a first approximation of the true processes that occur in the flare region since all elements have charge states greater than +1 at temperatures above 6 10^4 K. Hence, we take into consideration more realistic charge states of particles under solar conditions. Several studies have shown that carbon, nitrogen, neon, silicon and argon are only weakly enhanced at low energies (< 5 MeV/nucleon) in large flares. They also have relative abundances which are very similar to the photospheric abundances and show little variation from flare to flare. Based on the assumption that these characteristics are due to the fact that the source acceleration mechanism is unable to distinguish between these elements due to similarity in their charge to mass ratio in the ambient medium, a source region temperature of 6 ± 1 10^5 K is indicated (Vahia, 1987). This suggestion agrees well with the direct measurement of the solar cosmic ray charge state by Hovestadt et al (1984). The direct measurements indicate that the element charge states fall into two distinct components one with a mean temperature of 5 to 8 10^5 K and another of temperature around 2 to 5 10^6 K which corresponds to the temperature of particles picked up during passage through the corona. The fact that this is true for several large flares studied by a variety of techniques and at various times indicates that this is a common feature of large flares and therefore, by implication, that the large flares arise in regions of temperature about 6 10^5 K. This temperature is below the coronal temperature and therefore, the solar flare plasma separation must be occurring in lower chromospheric regions from which they rise into the coronal region.

The most common feature of the solar flares is the time varying magnetic field in the active regions. The most likely acceleration mechanisms in the active regions therefore are the stochastic and reconnection acceleration. We calculated the efficiency of the stochastic and the reconnection processes based on the assumption that the volume of the acceleration region is 10^8 cm^3, the magnetic field of the Solar flare acceleration region is 10^3 G and the electron density is 10^{14} p cm^{-3}. The basic formulation of Sorrell (1983) for the reconnection process and of Hillas (1984) for stochastic acceleration process are used. The calculations show that while the stochastic acceleration can give a maximum energy of 10^{13} eV, its time scales of 10^6 sec are far too large. On the other hand the time scales of reconnection, of the order of 50 seconds, agrees well with the time scales of the impulsive phase of solar flares and can give a maximum energy of 10^9 eV. This is more in agreement with the direct observations of particles up to 1 GeV in solar flares. We therefore discuss the reconnection process in some detail. In particular, in Vahia (1986) the details of the betatron process are discussed with the emphasis for accelerating solar flare particles. We use the boundary conditions that the magnetic field strength changes from 100 to 3000 G in 100 seconds. These values are within the observed variations of the magnetic field strengths in flare regions compiled by Priest (1984) which shows that flux changes of the order of 10^{19} Mx/hr can occur in active regions. From such calculations it can be seen that this results in a runaway acceleration of the particles and is most effective for temperature of 6 10^5 K (Vahia and Rao, 1987). However, in that work the energy loss processes were neglected. The comparison of the acceleration mechanism against the energy loss process are given in figure 1. The energy loss formulation is taken from Perez Peraza (1981) and the energy gain process is taken as the betatron process from Vahia (1986)(see also Vahia and Rao, 1987). Since the pp collisions have a crossection of about 40 mbarns at this energy, the energy loss by collision can be neglected. We discuss the implication of this figure in the three cases, when the electron density is less than 10^7 p cm^{-3}, when it is around this value and when it is greater than this value.

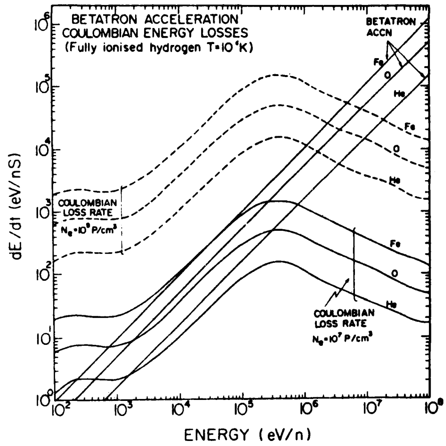

Fig. 1: Comparison of energy gain and loss processes in flare regions.

<u>Case 1: Large Particle Flares:</u> When the particle density is less than 10^7 p cm^{-3}, the particle acceleration rate exceeds the energy loss rate and, as a result, the active region will see a large release of particles as the plasma exceed the magnetic pressure. Since such low density is seen in upper coronal region only, the active regions must have large, stable and energetic loops that rise high into the corona before the final acceleration releases the particles. This feature is invariably seen in the active regions that release large flux of particles. The particle escape from such a loop can occur either from opening of the lines of force to the interplanetary medium or by rigidity dependant escape mechanisms (Vahia, 1986).

<u>Case 2: Intermediate Flares:</u> When the electron density is around the critical value of 10^7 p cm^{-3}, the region as a whole will not release particles but small heterogeneities in such a system can produce runaway acceleration and special selectivities that are characteristic of small flares.

<u>Case 3: Thermal Flares:</u> When the active region has electron density in excess of the critical value, practically no particle release would occur from such regions and all the magnetic energy would be converted into heat energy. However, in such cases also, the particles can continue to mediate in the active region in converting the magnetic energy into thermal energy.

Hence, if the above discussed processes have any relevance to the solar active regions, the particle population in such regions and the densities of such regions may be the critical deciding factors in forming a large particle flare, a small flare or a purely electromagnetic event. Also, if the above suggestion is true, the energy release in various types of events should show a clear correlation which can be derived from physical parameters that can be directly associated to the active regions.

Three kinds of classifications of the solar flares is made in the literature. The first, large flares are conspicuous by particle energy release of the order of 10^{31} ergs compared to electromagnetic radiation of the order of 10^{28} ergs (cf Hakura, 1976). The second class of events are associated with active regions that show a small amount of energy are known to show an enhancement in the He^3/He^4 ratio and are known as He^3 rich solar flares (cf Reames et al, 1988). The third class is that of active regions that show intense electromagnetic emission without any accompanying particle release. Detailed features of the three classes of events also agree well with the classifications made on the basis of direct observation by Bai (1986) for flares analogous to cases 1 and 3 and by Reames et al (1988) for case 2. The salient features of these observations are given in table 1.

Table 1 Observed features of Some classes of flares

Type of Event	Flare Size	Electron Density	10 MeV IP P Flux	Case
Gradual[1]	$>10^9$ cm	$<10^{7*}$ cm^{-3}	$>10^1/cm^2$ s sr MeV	1
He^3 flare[2]	$\sim 10^9$ cm	10^8 cm^{-3}	$\sim 10^{-2}/cm^2$ s sr MeV	2
Impulsive[1]	$<10^9$ cm	10^{11-12} cm^{-3}	$<10^{-2}/cm^2$ s sr MeV	3

[1] Bai(1986); [2] Reames et al (1988) *-Based on density in upper coronal region

Conclusion: We discussed the abundance patterns of solar cosmic rays and considering the similarity in abundance patterns derived a common temperature condition for them. We have then used the betatron mechanism, which is most effective at this temperature and attempted to derive the condition under which the acceleration becomes a runaway feature and the case when the acceleration may produce a purely electromagnetic flares. We have attempted to show that the entire feature arises from the same physics with the only difference being in the physical condition of various active regions. We then compared the observations and show that the flare classification suggested here is in good agreement with those made empirically from observational data.

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DISCUSSION

SMITH: As far as I can see your generalized reconnection is nothing more than an E-Field along the B-Field, but you cannot cite a specific mechanism. Is this true?

VAHIA: The generalised calculations given here are an attempt to estimate - by order of magnitude - the efficiency of various processes. It is not an attempt to determine or identify a specific process.

KUIJPERS: You said that the particle density in the loop determines whether the particles are released or not into the interplanetary medium. What is the physical process which lets the particles escape from the loop and how does it depend on density?

VAHIA: The critical factor that decides whether particles are released or not is the energy gain to loss rates. If the energy gain rate exceeds the energy loss rate (when the density is less than 10^7 cm^{-3}) there will be a runaway acceleration and in this case the particles will escape; either when their gyroradius becomes larger than the loop diameter or when the lines of force open to the interplanetary medium. Conversely, if the energy loss rate exceeds the energy gain rate, then all the energy put into particles will be converted into electromagnetic radiation.