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Chol-Jun Kim

An Interpretation of a Peculiar Correlation between Proton Events and H_α-Flares in the Context of Unsteady Reconnection

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Abstract. In a previous work, a specific correlation between proton events and related H_α-flares was discovered. According to that, in a H_α-flare importance diagram, H_α-flares accompanying the proton events were distributed on upper triangle of the diagram divided by the diagonal spanning SF and 3B signatures. Observational data published thereafter show the same specific correlation as in the previous work. The specific correlation has been interpreted by a competition between direct current electric field (DCEF) acceleration of ions and ion-anisotropic kinetic instability in the acceleration site through unsteady magnetic reconnection. On account of this mechanism, we can explain the observational facts that H_α-flare signatures 3N, 3F, 2F and 1F do not accompany proton events at all or almost do not and, on the contrary, the small and weak signature as SF accompanies a few proton events.

keyword: solar flare; solar proton

1. Introduction

Proton flares are known to be closely associated with strong, bright H_α-flares, in particular, with two ribbon flares. Observations over the past more than 30 years, however, have shown that even flares as faint and small as SF(H_α-flares) may give modest proton events (Molchanov, 1984; Kurt *et al.*, 2004; see below, Section 2)

In previous work(Kim *et al.*, 2001) we examined a possible correlation between proton events and related H_α-flare signatures and found that there exists a peculiar correlation between them. That correlation is characteristic by triangle feature of the distribution on H_{α}-flare signature diagram as we can see in Table 1, below. The table shows that H_{α}-flare signature 3N known as comparatively strong and large flare does not almost accompany proton events whereas H_{α}-flare signature SF known as weak and small flare is accompanying as many as 17 proton events.

Such a specific correlation must reflect some essential contents of the acceleration process of protons.

Even until a few tens of years ago, high energy proton events have been believed to be associated with coronal and interplanetary shocks. However, the recent investigations have shown that a majority of proton events has to do with magnetic reconnection in the flare site.

Belov *et al.* (2005) investigated a broad range of phenomenology relating proton events to X-ray flares amounted to 1144 proton events to >10MeV energy during 28-year period and concluded that the assumption that the initial proton acceleration occurs at the same time and place as associated flare is not inconsistent with their studies.

Many recent works on the proton acceleration are based on the direct current electric field (DCEF) generated in flaring region (Hamilton *et al.*, 2003; Podgorny *et al.*, 2010; Podgorny *et al.*, 2011). Podgorny and Podgorny (2006), comparing a model of a solar flare with observations of high energy processes, have shown that the exponential spectrum of relativistic protons generated during flare is consistent with acceleration by the electric field during the current sheet decay.

In this paper, we intend to find a justification of the electric field acceleration of protons from another observational fact and to confirm authenticity of the observational correlation found in Kim *et al.*(2001)

Kim *et al.* (2001) investigated proton events of a period 1970-1980 and found a peculiar connection between proton events and their identified H_{α}-flare signatures.

In Table1, the diagram which reveals the peculiar correlation between proton events and their identified H_{α}-flare signatures is presented (Kim *et al.*, 2001) in order to compare it with the recent observations.

The thresholds of proton detector for energy and flux are 5MeV and 0.1p.f.u., respectively(1p.f.u.=1 particle/$cm^2 \cdot s \cdot Sr$)

Table1. Number distribution of proton events identified with H_α-flares in H_α-flare signature diagram (1970-1980)[Kim *et al.*, 2001].

H_α-flare	S	1	2	3
B	33	84	57	14
N	34	56	21	2
F	17	3	2	0

As we can see in Table 1, proton events occur only in the upper triangle of the diagram divided by the diagonal spanning the H_α-flare signatures 3B and SF, and the lower triangle consisted of the H_α-flare signatures 1F, 2F, 3F and 3N which include only 2% of proton events (7/323) almost do not accompany proton events. Second finding in Table1 was that even in the small and faint H_α-flare as SF, proton flares could occur contrary to previous expectation.

Kim *et al.* (2001) attempted to explain the specific correlation in terms of combined operation of both electric field acceleration, on the other hand, and ion-anisotropic instability, on the other hand. Kim *et al.* (2001) made use of the stationary reconnection model of current sheet. However, the bursty and intermittent pulses seen in hard X-ray and radio wavelengths during the impulsive phase can only be explained unsteady magnetic reconnection model (Aschwandan, 2002). Actually, the numerical MHD simulation (Malara *et al.*, 1992; Kliem *et al.*, 2000) reproduce iterative fragmentation of the current sheet and this feature of dynamic current sheet evolution can reproduce fast modulation of particle acceleration on the right time scales (subsecond) observed in hard X-ray and radio waves. In this paper, we modify the steady reconnection model to fit for the fragmented bursty reconnection.

In Section 2, we present the observational data appeared in subsequent publications and compare them with previous result. In Section 3, we modify a bit the stationary model in accord with the unsteady reconnection. In Section 4, we summarize the results.

2. The Recent(subsequent) Observations

To testify the authenticity of the observational correlation found in Kim *et al.* (2001) we investigated the subsequently published data concerning the proton events. Table 2 presents the data of proton events for a period 1976-1997[Solar Gravitational Data (SGD), 1998].

The thresholds of proton detector for energy and flux are 10MeV and 10p.f.u., respectively.

Table 3 presents another observational data for a period 1970-2002 and the thresholds of detector for energy and flux are 10MeV and 10p.f.u., respectively.

The data of Table 2 and 3 cover more than 20 years (1976~1997) and 30 years (1970~2002) respectively, whereas the data of Table 1 cover 11 years (1970~1980).

Nevertheless, the total numbers of proton events in Table 2 and 3, respectively, are less than in Table 1. This is because of the fact that the flux threshold in Table 1 is 100 times as less as the cases of Table 2 and 3.

Table 2. Number distribution of proton events identified with H_α-flares in H_α-flare signature diagram (1976-1997)[SGD, 1988].

H_α-flare	S	1	2	3
B	1	7	34	32
N	1	7	11	0
F	3	2	0	0

Table 3. Number distribution of proton events identified with H_α-flares in H_α-flare signature diagram (1970-2002)[Kurt *et al.*, 2004].

H_α-flare	S	1	2	3
B	1	33	62	46
N	8	38	21	1
F	1	4	1	0

As we can see in Table 2 and 3, the upper triangle feature of the distribution of the H_α-flares accompanying the proton events is almost the same as in Table 1. A distinguished feature of Table 2 and 3 from Table 1 is that the H_α-flare area signature S in Table 2 and 3 have much less numbers of H_α-flares accompanying the proton events than in Table 1. As we will give an interpretation in next Section, this is because of the difference in the thresholds of energy detection.

A common character of the three Tables is that the H_α-flare signatures 3N, 2F and 3F do not accompany proton events at all or almost do not and the signature 1F does also almost not. In other words, H_α-flares accompanying the proton events lie on the upper triangle of H_α-flare importance diagram divided by diagonal spanning H_α-flare signatures 3B and SF, whereas the lower triangle which is consisted of 1F, 2F and 3N is not almost related to proton events and, especially, 3F is not at all.

Such a number of observational characters of the peculiar correlation is believed to imply and to reflect some essential physical aspects latent in the proton flares.

3. Unsteady Magnetic Reconnection and DC EF Acceleration

Kliem (1994) has considered the current filaments (magnetic islands) that are naturally formed by tearing instability in a reconnection region with enhanced resistivity.

Filamentary current sheet includes multiple X-points and intervening magnetic islands with O-points. Kliem has numerically computed particle motion for the configuration of two approaching magnetic islands. Its motion was mainly due to perpendicular electric field which consisted, in turn, of two components: one component results from lateral inflow motion and other one is induced from the approaching motion of the coalescing magnetic islands. Thus, the perpendicular electric field is convective: $\mathbf{E}_\perp = -\mathbf{v}\times\mathbf{B}$, where $\mathbf{v}$ is velocity of the convective mass flow.

Another scenario of particle acceleration by DCEF is acceleration in flare seat by an explosive coalescence of two approaching loop system (de Jager and Sakai, 1991; Sakai and de Jager, 1991). Through a numerical simulation, Sakai(1992) had shown the high effectiveness of particle acceleration by DC electric field around moving X-point magnetic fields, the electric field rapidly increases by as much as 10^4 times during a few seconds, and this leads to the acceleration of proton up to 10GeV for a millisecond. Then the generated electric field is also mainly perpendicular to magnetic field.

After a flare is triggered in a reconnecting region, the generated DCEF is

$$\mathbf{E} = \mathbf{j}/\sigma^* - \mathbf{v}_{in} \times \mathbf{B}_0$$

, where $\mathbf{v}_{in}$ is the convective velocity of plasma in magnetic field $\mathbf{B}_0$ and σ^* is and anomalous conductivity in the reconnecting region.

In this paper, we will not develop a detailed acceleration mechanism for protons and only adopt the previous theories of DCEF acceleration of protons in a completely collisionless plasma (Benz, 1993; Aschwanden, 2002). However, as pointed out in Section 1, we must take account of the fragmented structure of reconnection region. Instead of the stationary reconnection regime, fragmented current sheet caused by the tearing and coalescence instabilities makes the accelerating electric field more complicated and inhomogeneous (Aschwanden, 2002). Nevertheless, we can define a mean electric field <E> in the fragmented accelerating regions (or islands).

According to observation of hard X-ray and radio wave (Benz *et al.*, 1994; Benz, 1985; Benz, 1986) a high-degree of spatio-temporal fragmentation(up to 10^4) per a flare may be interpreted as a signatures of the fragmented energy release and acceleration region consisting of elements with size of ≦10^5m and time scale ≦50ms.

In order to interpret the peculiar correlation between proton events and related H_α-flares signatures as in Section 2, we adopt, as in Kim *et al.* (2001), the hypothesis that the proton flares are generated through a competition between DCEF acceleration of proton and ion-anisotropic microinstability. However, unlike Kim *et al.* (2001), we take the fragmentary structure of the reconnecting current sheet into account.

Figure1 presents a diagram where the abscissa denotes the acceleration energy of a proton and the ordinate indicates the characteristic time(CT) of acceleration $\lg t_E$ which depends on the kinetic energy ε_k, magnetic field B_0 and plasma inflow velocity v_{in} as follows(Kim *et al.*, 2001).

$$t_E = \frac{\left(mc^2 + \varepsilon_k\right)\varepsilon_k}{eB_0 v_{in}\sqrt{2mc^2\varepsilon_k + \varepsilon_k{}^2}} \tag{1}$$

(In Fig. 2 of Kim *et al.*(2001), the curves of the CT of DCEF acceleration are depicted, making use of the nonrelativistic relation (2), below. Here Figure 1 shows full relativistic CT curves.)

In nonrelativistic approximation, it reduces as follows

$$t_E = \frac{\sqrt{\varepsilon_0}\sqrt{\varepsilon_k}}{\sqrt{2}eB_0 v_{in}}. \tag{2}$$

As we see in the relation (1), magnetic field B_0 and plasma inflow velocity v_{in} enter the relation with the same right and they determine the intensity of flare. The horizontal line in the diagram represents the CT of the ion-anisotropic microinstability γ^{-1}. The condition for the accelerated protons to escape the acceleration region is $t_E < \gamma^{-1}$, and if opposite relation, $t_E > \gamma^{-1}$, is satisfied, the proton flares can't occur and the energy acquired by the particles would be transferred into development of the instability.

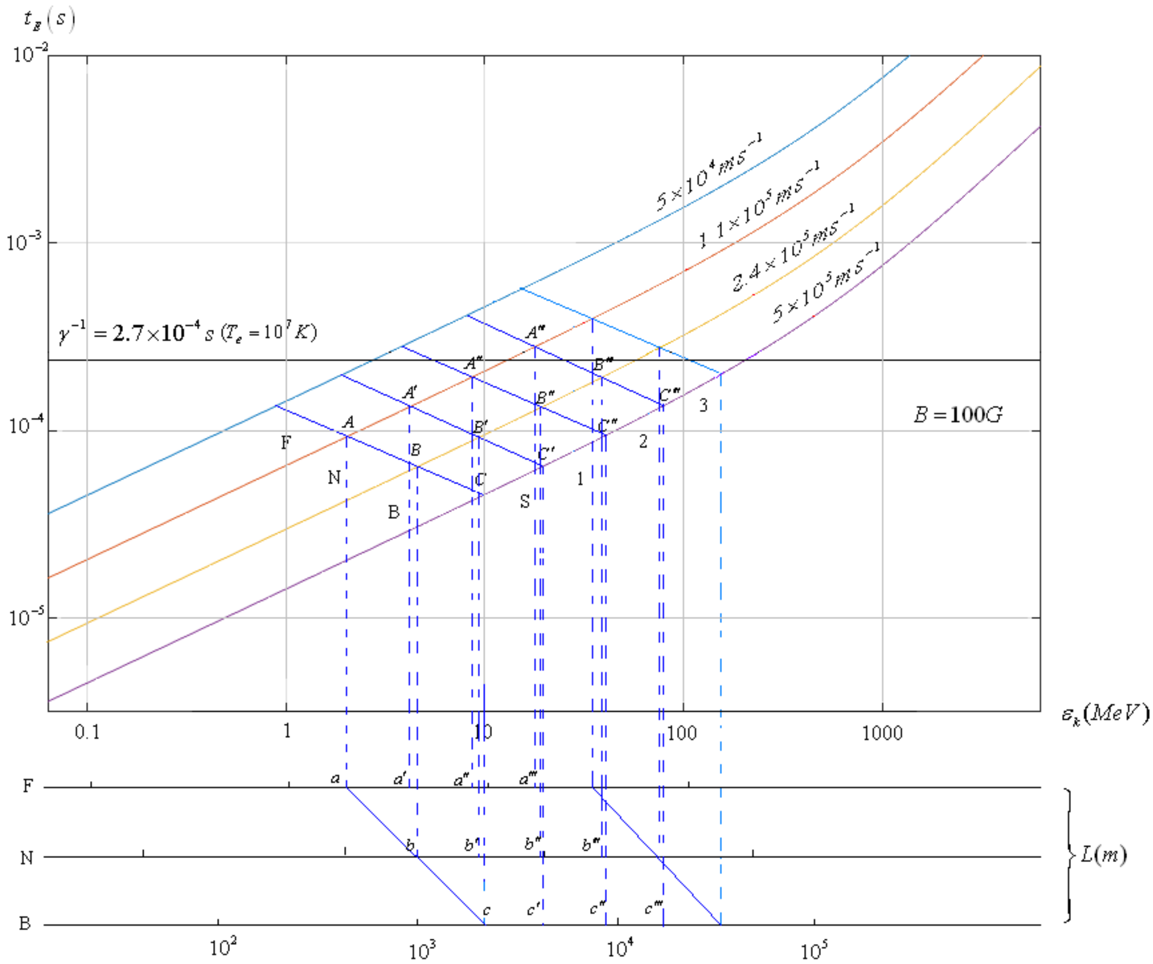

Figure 1. Characteristic time of acceleration t_E versus accelerated energy of a proton ε_k

In Figrue 1, the CT of DCEF acceleration increases with kinetic energy, but as soon as the CT of DCEF acceleration exceeds the CD of microinstability γ^{-1}, the microinstability halts the acceleration of protons and the instability develops. Hence, the region above the line of CT γ^{-1} is a domain where the proton flares can't occur and is forbidden. Therefore, the H_α-flare signatures 3F, 3N and 2F where H_α-flares do not or almost do not accompany proton flares may be associated with this domain of the diagram.(Kim *et al.*, 2001)

The signatures of flare-intensity, B, N and F are natural to attribute to different values of magnetic field B_0 or plasma inflow velocity v_{in}. Consequently, we can assume, for example, a correspondence between the H_α-flare intensity signatures B, N and F and the plasma inflow velocities, as given in Figure 1 for $B_0 = 100G$.(Kim *et al.*, 2001)

As we can see in the diagram of Figure 1, the plasma inflow velocity v_{in}=10^5m/s for B_0=100G can't yield protons with more energy than about 10MeV and the inflow velocity v_{in}=5×10^5m/s for B_0=100G can't also yield protons with more energy than a few hundreds of MeV. Likewise, in order for the proton flare with more energy than 1GeV to occur, the plasma inflow velocity v_{in}>10^7m/s for B_0=100G or the magnetic field of a few hundreds Gauss for the inflow velocity v_{in}=(10^5-10^6)m/s need. This is due to a restriction from the microinstability. In other words, only in terms of the increase of acceleration length one can't achieve the increase of acquired energy of protons.

Because, in the diagram, $<\lg\varepsilon_k - \lg t_E>$ of Figure 1, symbols S, 1, 2 and 3 indicate the H_α-flare area signature, then the area signatures can replace by acceleration length or accelerated energy. (Kim *et al.*, 2001) The equally spaced three lines representing the acceleration length, under the diagram of Figure 1, give a possibility of comparing the acceleration length and time with observation.

As we pointed out in the above, observation of hard X-ray and radiowaves indicate a high-degree of spatio-temporal fragmentation (up to 10^4) per a flare and such phenomena may be interpreted as a signature of the fragmented energy release and acceleration region consisted of elements with size of $\leq10^5$m and time scale 50*ms*.

According to Fig. 1, the acceleration length 10^5m of an element corresponds to 500*MeV* of energy in B-signature of H_α-flare, to 240*MeV* in N-signature and to 110*MeV* in F-signature. Similarly, the acceleration length 10^4m corresponds to 50*MeV* in B-signature, to 24*MeV* in N-signature and to 11*MeV* in F-signature. However, in the plasma inflow velocity (magnetic field) as in the diagram, protons can't be accelerated upto the length of 10^5m because ion-anisotropic instability prohibits the acceleration as one can see in Figure 1. If we extend the plasma inflow velocity to (10^6-10^7)m/s (in B_0=100G) or magnetic field to 500G, then within less time of acceleration than the CT of instability, say, about a few 10^{-4}s, the acceleration length may be increased over 10^5m and one can achieve high energy of protons but at the cost of increase of plasma inflow velocity or ambient magnetic field because the small plasma inflow velocity(or magnetic field) does not allow the increase of energy because of the anisotropic instability.

The acceleration CT is maximally (10^{-4}-10^{-3})s regardless of the acceleration energy of protons because it is limited from upside due to the CT of instability γ^{-1}, which is in accord with observed time scale of acceleration ≦50ms. This time limit is determined on account of the temperature of reconnecting current sheet. ($\gamma^{-1}=2.7\times10^{-4}$s for $T_e=10^7$K and $\gamma^{-1}=6.8\times10^{-5}$s for $T_e=10^8$K) Here, we should point out the fact that the time scale of hard X-ray and radiowaves and the acceleration time of particles can't be regarded in the same light, and the observed time scale of hard X-ray and radiowaves may be longer than the acceleration time scale. Therefore, the short time for the acceleration as compared with time scale of hard X-ray is reasonable. The observed time scale of hard X-ray only sets up the upper limit of the acceleration time.

Thus, the fragmented bursty structure of reconnecting current sheet and the short length and time scales (≦10^5m and ≦50ms) are in accordance with length and time scales due to the competition between DCEF acceleration and ion-anisotropic instability[(10^4-10^5)m and (10^{-4}-10^{-3})s].

Of course, this accordance is fortuitous. In other words, the limiting of the acceleration length and time due to ion-anisotropic instability is not in a direct causal relation with the fragmented structure of the current sheet. Only can we say that the observation does not exclude the action of the ion-anisotropic instability introduced in above. Therefore, the more important in this paper is that, in a diagram on the H_α-flare signatures, a peculiar properties of the distribution of the H_α-flare signatures accompanying proton events are interpreted on account of the ion-anisotropic instability.

Finally, we must give an explanation to the fact that the area signature S in Table 2 and 3 contain less numbers than in Table 1. This fact may be explained on account of the difference of the detection thresholds of proton detectors. As mentioned in Section 2, Table 1 has a threshold of energy 5MeV and Table 2 and 3 10MeV. Therefore, as we can see in Figure 1, the signature S lie on the left side of energy 10MeV and this signature is approximately outside the detection range.

4. Conclusion

In our investigation of the specific correlation between proton events and H_α-flare signatures accompanying them, a basic confirmation is that the H_α-flare signatures 3F, 3N and 2F do not accompany proton flares or almost do not. We associate this observation with an instability of the accelerated ions. It is ion-anisotropic microinstability. A possibility of the generation of the ion-anisotropic instability in the seat of impulsive electric field acceleration by an explosive coalescence of two approaching loop systems is also conjectured in early studies(de Jager and Sakai, 1991; Sakai and de Jager, 1991; Sakai, 1992) as mentioned in Kim *et al.*(2001)

Another important confirmation is that, even in the small and weak H_α-flare as SF, proton flares could occur contrary to the common expectation. On the contrary, the H_α-flare signature 3N is believed to be strong and large as compared with the signature SF. Nevertheless, the H_α-flare signature 3N does almost not accompany the proton events while the signature SF accompanies, at least, a few proton events. This specific property of the signature SF may be easily expounded on account of the diagram of Figure 1. Thus, the competition between the proton acceleration by perpendicular DCEF and the ion-anisotropic instability formed due to the perpendicular acceleration, through a diagram, <lg(accelerated enerhgy)-lg(CT of acceleration or instability)>, renders an account of the important observed properties of proton events.

Thus, subsequent observations(after 2001) confirm the existence of the peculiar correlation between proton events and related H_α-flare signatures, and the explanation of it by DCEF acceleration justifies the common understanding on the proton acceleration from an another observational fact.

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