THE STARTING CONDITIONS FOR AN OPTICALLY SMALL SOLAR GAMMA RAY FLARE

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ABSTRACT

We suggest that optically small γ-ray flares result from gradual pre-flare acceleration of protons over $\sim 10^3$s by a series of MHD shocks in the low corona. A fraction of the accelerated protons are trapped in the corona where they form a seed population for future acceleration. If the shock acceleration is sufficiently rapid proton energies may exceed the γ-ray production threshold and trigger γ-ray emission. This occurs without the total flare energy being necessarily large. Magnetic field geometry is an important parameter.

1. Introduction

Now that the statistics of γ-ray flares have improved to the point where meaningful comparisons can be made with other flare data it has become clear that not only the large, spectacular Hα flares are associated with prompt nuclear line emissions (e.g., ^{12}C and ^{16}O). Such flares require the presence of protons > 10 MeV and generally exhibit the p(n,γ)d neutron capture line requiring protons $\gtrsim$ 30 MeV. Results from SMM [1] have shown that a significant portion of the γ-ray events have onset times of γ-rays and hard X-rays (> 28 keV) coincident to within ∿ 1 s with the total hard X-ray integrated flux well correlated with that of the γ-rays [2]. A process for producing hard x-rays from γ-ray producing protons is discussed in another paper [3]. Our model for such flares must be capable of producing such quasi-simultaneity, and it should also be capable of delaying γ-ray production without having to resort to a separate model. In extreme cases there is evidence of proton (ion) acceleration up to 1 GeV within a few s of the hard X-ray onset [4].

If we concentrate on the more common case where protons only up to 30 MeV are required, this still represents a significant energy gain if the protons start with a thermal distribution at ∿ 10^7K (1 keV). Although mechanisms have been examined theoretically to achieve such rapid accelerations [5], the necessary physical conditions for the required acceleration efficiency are very severe and appear to be improbable at the Sun. We suggest that such rapid acceleration is not necessary, and that γ-ray emission represents the end product of a much more gradual (∿ 10^3 s) acceleration process.

2. The Acceleration of Protons

There are few observational constraints on proton acceleration up to ∿ 1 MeV, somewhat below the γ-ray production threshold. However, we know from range/energy considerations that the acceleration cannot take place at high densities, thus restricting the acceleration site to the high corona. For example, at a density of 2×10^9 cm^{-3}, which is representative of the base of the corona [6], a 100 keV proton has a range of only 4×10^9 cm, which it would cover in $\sim$ 8 s. Therefore not only would any acceleration process at these densities result in excessive heating - most of the available energy would be dissipated as heat - but protons which did manage to get accelerated to 100 keV would have a short lifetime. However, a 400 keV proton has a range of 10^{12} cm at a density of 10^8 cm^{-3}, and therefore a lifetime $\sim 10^3$ s. From these considerations we suggest that any proton acceleration region should be at a density at least as low as 3×10^8 cm^{-3} corresponding to an altitude of $\sim 10^5$ km. We believe the most plausible mechanism for proton acceleration is coronal shock acceleration. The basic theory of particle acceleration in shocks has been given by Bell [7] and most subsequent work has developed from his suggestions.

Fig. 1 outlines the scenario that appears most appropriate for the development of γ-ray flares. The magnetic field configuration is likely to be complex, with a series of small scale loops (shown left inset), plus some overlying magnetic structure with an overall size $\sim$ 10^5 km. We suggest that evolution of the lower lying loop structure, possibly caused by emerging flux, causes small energy releases, heating and a succession of small shocks. A fraction of the protons accelerated in these shocks are trapped in the overlying field and are available for further acceleration as seed particles in subsequent shocks . The acceleration we believe requires and is enchanced through the development of resonant turbulence, illustrated schematically in the center inset of Fig. 1. Throughout the whole process there is feedback between the accelerated particles, the MHD waves and shocks. This drives the energy release process harder. The latter is probably due to induced additional magnetic field reconnection. In the γ-ray

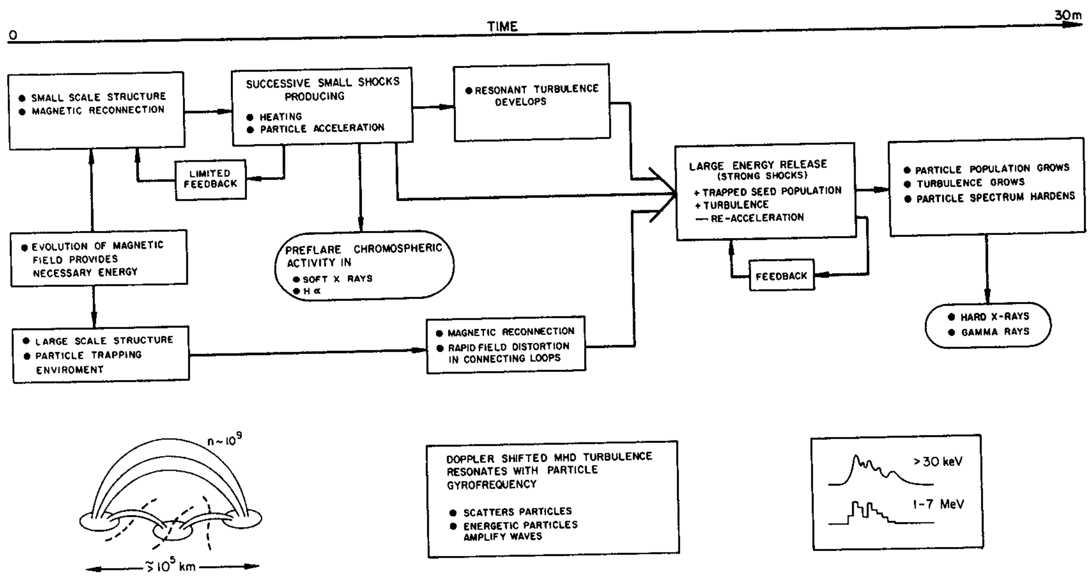

Figure 1. Schematic of pre-flare and flare particle acceleration and activity.

flare the build up of the proton population is eventually sufficient for a significant precipitation of protons near or below the transition zone, producing the signature of a γ-ray flare. This is illustrated schematically in the right inset of Fig. 1. The whole process takes ∿ 10^3 s. This is consistent with the coronal acceleration model discussed by Lee and Ryan [8].

There are some observable consequences of the scenario we have outlined. First, some of the more energetic protons from the early accelerations will not be stably trapped but will impact the top of the chromosphere, causing heating but little else. This heating should be visible prior to the flare as small soft X-ray and EUV brightenings from the appropriate impact points along the base of the loops indicated in the left inset (Fig. 1). Second, the protons that are stably trapped will, in fact, continue to lose energy to the coronal gas, thereby heating it. It has recently been suggested [9] that such heating may destablize a coronal mass ejection, thus opening the magnetic field and releasing the trapped protons. This would also drive the energy release harder, causing a flare but probably not a γ-ray flare because the particle trapping environment has been lost.

3. Supporting Observations

The model is well supported by observations of the M4 γ-ray flare near the solar limb on 1980 June 29, 10:41 UT. Fig. 2 shows the intensity-time profile of 3.5-8.0 keV X-ray, emission from 10:20-10:45 UT. The onset of the impulsive phase we take to be 10:40:10UT. It is obvious from the soft X-ray observations that there was considerable pre-flare activity for some 20 m before the impulsive phase. The OV transition region UV line intensity exhibits the same general behavior while hard X-rays and γ-rays are undetectable until after 1041 and peaking at about 1042. Spatially resolved data show that there were a number of resolved bright points in OV over a region of the limb covering a projected distance of > 10^5 km. A large X-ray emitting structure extending ∿ 1.5 x 10^5 km above the limb (in projection) was reported for the period of June 29 [10].

The general conclusion from these data is that before the γ-ray flare there was non-impulsive, but substantial emission from the transition zone over a widespread area near the solar limb. There was also evidence of a large scale magnetic structure of the type we believe is suitable for trapping moderate energy protons (few hundred keV) for periods of many minutes. Although there is some evidence for small disturbances in the corona during the flare, there was no major coronal transient as there was from other non-γ-ray flares from this region.

Prior to the impulsive phase significant plasma turbulence was observed in Ca XIX emission indicating random velocities > 150 km/s. Also there is very little evidence of radio emission before the impulsive phase. This is all consistent with energy deposition and wave generation by non-thermal protons in the low corona. Clearly this is a feature of our gradual acceleration model, which would predict proton energies of a few hundred keV, which are sufficient to drive the plasma turbulence, some 10s of seconds before the 10 MeV energies required for the γ-rays.

4. Conclusions

We believe that the mechanism resulting in γ-ray emission from an otherwise optically small flare is the slow build-up of particle energy

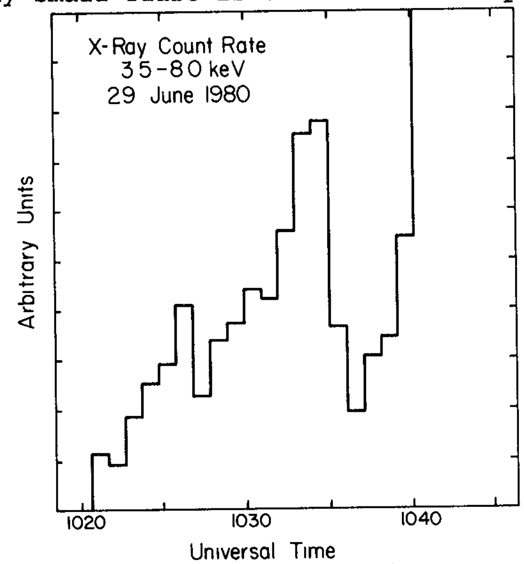

Figure 2. Soft X-ray count rate measured by HXIS on SMM. The impulsive phase is well off scale.

over a time scale of 10^3 s before the impulsive phase. The magnetic field configuration is very important and requires the presence of stable magnetic structures in the corona reaching to altitudes in excess of 10^5 km. Such magnetic structures are used to trap accelerated particles. During the pre-flare period energy is transferred to non-thermal protons by a series of small MHD shocks, gradually re-accelerating the surviving protons. A signature of this acceleration is the excitation of weak EUV and soft X-ray emission where some of the accelerated protons impact the chromosphere.

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6. References

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