ION ENERGY STORAGE FOR POST-FLARE LOOPS

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ABSTRACT

Low-energy non-thermal protons may have long lifetimes in coronal loops with low density and high temperature. If energy were stored in such protons in the initial phases of a solar flare, it could be released slowly during the later phases. Within the present observational limits for post-flare loops, this mechanism should be considered in addition to a field-line reconnection theory of the Kopp and Pneuman type. The thin-target γ-ray emission from the trapped protons is below present limits, but more sensitive observations can test the hypothesis.

1. Introduction. Solar flares consist of distinct impulsive and gradual phases[1] plus other associated phenomena. The impulsive phase exhibits powerful energy release and particle acceleration. The gradual phase - the period of main Hα and soft X-ray emission - may also require energy release, although on a slower time scale. The need for this energy release is seen in the gradual growth of the soft X-ray loops of the gradual phase[2] interpreted as a sequential excitation of independent flux loops. Although greater uncertainties exist, theoretical estimates of cooling times also suggest gradual energy release[3] within a given loop. The gradual phase also has a strong association with the acceleration of the coronal mass ejections and the copious production of interplanetary particles[4], so that non-thermal processes must continue during this phase.

The role of energetic protons in solar flares has a long history, stimulated by the observation at Earth and in the interplanetary medium of the "solar cosmic rays." Elliott[5] propounded the idea of energy storage in protons, taking advantage of long Coulomb-scattering lifetimes. The difficult point about understanding the role of protons in the flare proper has remained their essential un-detectability: basically only those particles above thresholds near 10 MeV produce γ-ray spectral line emission, and even this has only generally been diagnostically useful for solar flares since the launch of the Solar Maximum Mission in 1980. Other than theoretical inference from the interplanetary particles and from the high-energy γ-ray-emitting particles, at present we have only the possibility of optical spectroscopy as a means for remotely sensing flare protons at low energies[6-7].

2. An Ion Energy-Storage Scenario. As indicated by the γ-radiation, the impulsive phase of a solar flare powerfully accelerates energetic ions. This acceleration begins at about the same time as the non-thermal electron production of the impulsive phase, but may take place[8] in a "second step".

The scenario discussed in this paper simply is that bulk acceleration of energetic ions in flare loops adjacent to those of the impulsive phase may leave a non-thermal ion population in these loops. Coulomb scattering will then extract this energy from the ions and give it to the electrons, as long as the ions can remain stably trapped. The electrons couple the energy strongly into radiation or conduct it into the chromosphere. The main attractive feature of this scenario, aside from its simplicity, is that the excitation of post-flare loops follows a definite pattern of later loops having lower densities[9], which would have a natural explanation in terms of Coulomb collisions. This scenario of ion energy storage was first proposed by Jefferies and Orrall[10], but has not received much attention in the light of modern data.

3. Coulomb Scattering: Simple Physics. Coulomb scattering describes the physics of charged-particle interactions. The electrostatic force between two particles, one considered as a test particle and the other as a member of the background plasma, will change the energy and momentum of the test particle relative to the background. To apply the Coulomb collision theory, we must specify the velocity distribution functions of the test particles and field particles. In general, flare energy release should result in non-Maxwellian, anisotropic distributions. To avoid this complication, we assume here that the ion and electron components have separately relaxed to Maxwellian distributions characterized by temperatures T_p and T_e respectively. We further assume that the ions are protons. At low proton energies[11],

$$\tau_{pe} = 12.6\ T_e^{3/2}/n_e;$$

note that the equilibriation depends solely upon the temperature and density of the electron distribution. For a typical soft X-ray temperature of 10^7 K and a density of 10^{10} cm^{-3}, we have $\tau = 39.8$ s.

For proton energies exceeding (M/m)kT (1.57 MeV at $T_e = 10^7$ K), the time scale begins to increase approximately as

$$\tau_{pe} = 2.0 \times 10^{11}\ E_p^{3/2}/n_e,$$

with E_p in MeV. For example, at 10 MeV in a density 10^{10} cm^{-3}, we have τ = 632 s.

4. Coulomb Scattering: Complications. The discussion above describes the basic minimum physics of the interactions between differentially heated electrons and protons. Beyond this physics, other processes could play roles important to the question of energy storage: (i) Scattering. The trapped protons may escape by pitch-angle scattering into the loss cone. This scattering could occur as a result of Coulomb collisions or "anomalously" from interactions with waves[12-13]. (ii) Drift. Non-adiabatic motion may lead trapped protons into the loss cone or move them to open field lines[13]; this process depends crucially on the geometry of the flux tubes. (iii) Charge exchange. Low-energy protons can neutralize by picking up a free electron, thus permitting them to cross magnetic field lines and escape from a trap. (iv) Filamentation. If the post-flare loops

contain small-scale filaments, undetectable at present resolution, the higher density in the filaments would shorten the proton Coulomb lifetime.

These processes would in each case reduce the storage time of the protons, making their energy less likely as an explanation for the observed late-phase heating in solar flares. It is likely that pitch-angle scattering from ion-cyclotron waves, driven by the anisotropy of the loss-cone distribution of the mirroring trapped particles, would occur on time scales much shorter than the Coulomb energy losses[12]. Nevertheless the instability calculations are model-dependent and it is worthwhile to consider the Coulomb scattering alone, since this mechanism cannot fail to operate.

From the above estimates of time scales, we can draw the immediate conclusion that proton energy storage would not have long enough time scales for post-flare loops (100 -10000 s) except at low enough densities ($n < 10^8$ cm^{-3}) or for high enough proton energies; in the latter case the protons may be energetic enough to exceed the excitation thresholds and produce γ-ray emission.

5. Comparison with Observations. Gamma-ray Production. To compare the theoretical time scales with the observations, we examine the flare of August 21, 1973, for which MacCombie and Rust[14] have given estimates of the physical conditions in the post-flare loops. Density 5×10^9 cm^{-3} and temperature decay time of 1.7×10^4 s lead to a proton energy of 43 MeV. This energy is high enough to produce γ-ray emission lines from thin-target interactions as the protons bounce between the hypothetical magnetic mirrors.

The total number of trapped protons can be estimated from the total energy of the soft X-ray source. From the emission measure and density quoted by MacCombie and Rust, we find a total energy $W = 5 \times 10^{29}$ ergs. This requires about 7×10^{33} protons at 43 MeV. For the 4.43 MeV γ-ray line of ^{12}C, Ramaty *et al.*[15] give a cross-section of about 40 mb; assuming a carbon abundance of 1.6×10^{-4} relative to hydrogen, we would have a γ-ray flux of about 8×10^{-4} (cm^{2}sec)$^{-1}$. This is about one order of magnitude below the faintest reported solar fluxes[16], so that the energy could be stored in protons and not detected via its γ-ray emission.

6. Conclusions. Elliott[5] proposed the pre-flare storage of energy in energetic protons, based upon their long Coulomb time scales. This idea may still not conflict irreconcilably with observations, although the theoretical question regarding the impulsive nature of the primary flare energy release would remain unexplained. This problem may also exist for the post-flare energy storage hypothesis: experienced observers of Hα line spectra in flares have noted that distinctly unusual Hα profiles occur predominantly at the outer edges of expanding flare ribbons[17]. This implies fairly directly that non-thermal energy release takes place late in the flare development, and provides some of the best evidence in favor of the magnetic flux reconnection[18] as a cause of post-flare heating. These red-shifted or broadened hydrogen emission-line profiles have no simple

explanation in terms of the proton energy-storage hypothesis, since the energy release should occur gradually, but no detailed calculation of the energy transfer between the particle populations presently exists.

I conclude that the proton energy storage hypothesis could work from an energetics point of view. Sensitive γ-ray observations can test the hypothesis directly by observing the thin-target emission of the trapped protons. In the meanwhile, better knowledge of physical conditions in the flare soft X-ray sources would be helpful. Theoretically, further studies of the limits on stable trapping would form part of the necessary treatment of the complete evolution of a flaring loop. Even if ion energy storage turns out to play no role in post-flare energy release, such studies would be well worth while in view of the likelihood that ions and electrons will have different distribution functions.

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