Electron versus Proton Timing Delays in Solar Flares

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ABSTRACT

Both electrons and ions are accelerated in solar flares and carry nonthermal energy from the acceleration site to the chromospheric energy loss site, but the relative amount of energy carried by electrons versus ions is subject of debate. In this Letter we test whether the observed energy-dependent timing delays of 20-200 keV HXR emission can be explained in terms of propagating electrons versus protons. For a typical flare, we show that the timing delays of fast ($\lesssim 1$ s) HXR pulses is consistent with time-of-flight differences of directly precipitating electrons, while the timing delays of the smooth HXR flux is consistent with collisional deflection times of trapped electrons. We show that these HXR timing delays cannot be explained either by $\lesssim 1$ MeV protons (as proposed in a model by Simnett & Haines 1990), because of their longer propagation and trapping times, or by $\approx 40$ MeV protons (which have the same velocity as $\approx 20$ keV electrons), because of their longer trapping times and the excessive fluxes required to generate the HXRs. Thus, the HXR timing results clearly rule out protons as the primary generators of $\geq 20$ keV HXR emission.

Subject headings: acceleration of particles — radiation mechanisms: non-thermal — Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

Whether protons or electrons dominate particle acceleration and non-thermal energy transport in solar flares is still subject of recent debate [e.g. see Great Debate articles by Cargill (1996), Simnett (1996), and Emslie (1996)]. Moreover, proponents of proton-dominated models argue that even the $\geq 20$ keV HXR bremsstrahlung is produced either by protons directly (Heristchi 1986; 1987) or by proton-energized electrons (Simnett & Haines 1990). The purpose of this Letter is to complement these ongoing debates with powerful new arguments that are supported by observations of energy-dependent hard X-ray (HXR) timing delays in solar flares.

Electrons have been favored for the interpretation of impulsive $\geq 20$ keV HXRs because the inversion of the HXR spectrum (Brown 1971) in the framework of energy loss by collisional bremsstrahlung (in a relatively cold target) could easily reproduce: (1) an electron spectrum that contains the necessary and sufficient energy content to explain the non-thermal HXR emission, (2) the gyrosynchrotron emission observed at microwave wavelengths, and (3) the soft X-ray emission resulting from the heated, upflowing chromospheric plasma. More detailed arguments for the case of electron dominance in solar flare energy transport can be found in Emslie (1996), Emslie et al. (1996), and references therein.
Protons, on the other hand, have been invoked as primary energy carriers (Simnett 1986; 1995) mainly because it minimizes the number of energy-carrying particles (thanks to their intrinsically higher rest mass, i.e. $m_p/m_e = 1836$), which in turn also minimizes return currents (at least for high-energy protons with $E \gg 20$ keV, see, e.g., Simnett & Strong 1984, Emslie & Brown 1985). Observational support for the proton hypothesis was mainly gathered by indirect effects, e.g. (1) acceleration mechanisms (e.g. shocks) can have greater efficiencies for protons because of their larger gyroradii, (2) the proton spectrum at energies $\leq 10$ MeV could be considerably steeper than previously supposed (Ramaty et al. 1995), based on recent measurements of Share & Murphy (1995), (3) detection of interplanetary high-energy ($\geq 40$ MeV) protons (Evenson et al. 1984), etc. A discussion of arguments in favor of protons can be found in a recent review by Simnett (1995), and further arguments of proton versus electron beam models are discussed in Brown et al. (1990).

A new aspect that we would like to contribute to the electron-versus-proton debate is based on new timing results from HXR observations in solar flares, analyzed in a series of recent studies (Aschwanden, Schwartz & Alt 1995; Aschwanden & Schwartz 1995; 1996; Aschwanden 1996; Aschwanden et al. 1996a; 1996b; 1996c). The energy-dependent timing delays $\tau(E)$ of fast ($\lesssim 1$ s) HXR pulses during the impulsive flare phase have been found to be consistent with electron time-of-flight differences, while the timing delays of the smooth HXR flux are comparable with electron trapping time scales. The interpretation of hard X-ray time structures in terms of these two components (associated with directly-precipitating versus trapped particles) is a basic assumption used in the following discussion, in contrast to the widely-held hypothesis that the lower envelope of the rapidly-varying hard X-ray flux consists of an unresolved pileup of elementary pulses with similar characteristics as the rapid fluctuations (e.g. Kiplinger et al. 1983, 1984; Machado et al. 1993). While protons have not been considered in our previous studies, we would like to explore in this Letter whether proton theories could be reconciled with the observed HXR timing delays, and what the required proton energies would be. Because the timing delays of HXRs are directly related to the particle velocities, timing information provides a direct means of constraining the kinetic energy and rest mass of the involved particles.

In Section §2 we compare theoretical electron and proton time-of-flight differences with the observed delays of fast HXR pulses. In Section §3 we discuss theoretical trapping times in solar flare loops and compare them with the observed delays of the smooth HXR emission. Section §4 contains conclusions on the question of which species of particles is more likely to reproduce the observed HXR timing delays.

2. Particle Time-of-Flight Differences

Both proponents of electron-dominated and proton-dominated flare models agree with the assumption that particles are accelerated in the coronal part of a flare loop and that the HXRs observed from the loop footpoints are produced by collisional bremsstrahlung in the chromosphere. The main difference between the two models is the question of the particle species that carries the energy from the acceleration site to the energy loss site. In the case of proton-dominated models, either the protons produce HXR’s directly by inverse bremsstrahlung (Emstie & Brown 1985; Heritchi 1986; 1987), or a neutral beam is assumed to precipitate to the chromosphere, where an electric field arising from charge separation accelerates HXR-emitting electrons (Simnett & Haines 1990). In the latter model, electrons are thought to be stripped by Coulomb scattering from a neutralized ion beam as it impacts the chromosphere. This charge separation process may set up an electric field that is able to produce runaway acceleration of electrons responsible for the $\geq 20$ keV HXR bremsstrahlung. This model has been severely criticized by Emslie (1996).
Thus, the timing of the two models can be tested in first order by comparing the particle time-of-flight differences occurring during the propagation from the coronal acceleration site to the chromospheric energy loss site. If the energy-dependent timing delays of the HXRs is dominated by such propagation effects, the HXR emission produced by the low-energy particles should always be delayed with respect to the high-energy particles, because of their lower velocity. Energy loss times and acceleration times seem not to dominate the timing delays of $\gtrsim 1$ s HXR pulses in most of the flares, because they do not reproduce the correct sign in the energy-dependent timing delays (Aschwanden et al. 1996a; Aschwanden 1996). Thus, the time-of-flight difference $\tau_{ij}$ between two particles $i$ and $j$ arriving at the chromospheric energy loss-site is determined by their velocities $\beta_i = v_i/c$ (or $\beta_j = v_j/c$) and the path length $l$,

$$
\tau_{ij} = \frac{l}{c} \left( \frac{1}{\beta_i} - \frac{1}{\beta_j} \right) .
$$

The relativistic velocity $\beta$ is defined by the kinetic energy $E_{\text{kin}} = mc^2(\gamma - 1)$ of the particles and the Lorentz factor $\gamma = 1/\sqrt{1 - \beta^2}$, i.e.

$$
\beta(E_{\text{kin}}) = \sqrt{1 - \left( \frac{E_{\text{kin}}}{mc^2} + 1 \right)^{-2}}
$$

If we compare electrons with a kinetic energy $E_e$ and rest mass $m_e$ with protons of kinetic energy $E_p$ and rest mass $m_p$, the velocity ratio is

$$
\frac{\beta_p}{\beta_e} = \sqrt{\frac{1 - \left( \frac{E_p}{m_p c^2} + 1 \right)^{-2}}{1 - \left( \frac{E_e}{m_e c^2} + 1 \right)^{-2}}} \approx \sqrt{\frac{E_p}{E_e}} \cdot \frac{m_e}{m_p} = \frac{1}{43} \sqrt{\frac{E_p}{E_e}},
$$

where the right-hand approximation applies to the non-relativistic (or mildly relativistic) case. For instance, to obtain identical velocities for electrons and protons, the kinetic energy of the protons has to be a factor $m_p/m_e = 1836$ larger, e.g. 40 MeV protons have the same velocity as 20 keV electrons.

In the case of protons, it was proposed that flare HXRs could be produced by an "inverse bremsstrahlung process" (Boldt and Serlemitsos 1969; Emslie & Brown 1985; Heristchi 1986; 1987). Protons would produce HXR emission by collisional bremsstrahlung in collisional encounters with electrons. The relative velocity of a proton of energy

$$
E_p = \left( \frac{m_p}{m_e} \right) E_e
$$

in an encounter with an ambient electron is the same as that of an electron of energy $E_e$ in an encounter with a stationary proton. Since $\gtrsim 40$ MeV protons have identical velocities as $\gtrsim 20$ keV electrons, they would also show the same time-of-flight differences as observed. However, the major problem with $\gtrsim 40$ MeV protons is that the required proton flux to produce the observed $\gtrsim 20$ keV HXR flux would exceed the proton flux deduced from nuclear gamma-ray line observations (at 2-10 MeV) by a factor of $\approx 10^3$ (Ramaty 1985).

To alleviate the problem of 40 MeV protons, Simnett & Haines (1990) proposed a neutral beam model, that requires only 0.1-1 MeV protons to produce the observed $\gtrsim 20$ keV HXR flux. After a neutral beam arrives at the chromosphere, HXR emission is produced by secondary electrons accelerated in the electric field that arises from the charge separation of penetrating ions and thermalized primary electrons. Thus, the timing delays of HXR emission are mainly determined by the coronal propagation time of the 0.1-1 MeV protons in the neutral beam. However, these lower proton energies correspond to velocities that would produce far greater time-of-flight differences than for 40 MeV protons or 20 keV electrons. According to
Eq. 3, the velocity of 1 MeV protons would be a factor of \( \beta_p/\beta_e \leq (1/43)\sqrt{1/0.02} = 0.1 \) smaller than for 20 keV electrons, and thus, the time-of-flight differences would be 10 times larger than for 20 keV electrons or 40 MeV protons.

Fig. 1 shows typical HXR time delay measurements in the energy range of 40-300 keV for a major flare. The pulsed HXR flux (Fig. 1 bottom right) exhibits time delays of \( \tau(E) = t(40\text{ keV}) - t(E) \lesssim 50\text{ ms} \). These delays show the correct sign as expected for particle time-of-flight differences, i.e. the lower energies lag the high energies. Also the functional form of the energy-dependent time delay is consistent with the expected model (Eq. 1, thick line on right-hand side bottom in Fig. 1), within a high accuracy of \( \lesssim 10\text{ ms} \). For the conversion of electron energies \( E \) into HXR photon energies \( \epsilon \), a conversion factor of \( q_E = E/\epsilon \approx 2 \) was determined (see second line on right-hand side from bottom in Fig. 1, according to calculations in Aschwanden & Schwartz 1996). Moreover, the time-of-flight distance, i.e. \( l = 20,000\text{ km} \), is found to be close to a loop half length (\( s = 14,000\text{ km} \)), if electron velocities are employed. This ratio \( l/s \approx 1.4 \) was established to be scale-invariant for a comprehensive set of loop sizes in different flares (Aschwanden et al. 1996b, 1996c).

If we employ protons to reproduce these observed HXR delays, we can either adjust the energy range or the time-of-flight distance. If we adjust the energy range, protons with energies of \( \geq 40\text{ MeV} \) would be required to produce matching velocities. If we employ 1 MeV protons, the velocities would be 10 times smaller, thus requiring a time-of-flight distance 10 times shorter to satisfy the same timing delays (Eq. 1; also depicted in Fig. 1 middle right). Based on the statistics of flare loop sizes (typically with loop radii of \( \lesssim 20,000\text{ km} \), Aschwanden et al. 1996c), a time-of-flight distance 10 times smaller (\( l \lesssim 2000\text{ km} \)) would be comparable with the height of the chromosphere, requiring an acceleration site located near the transition region. Such a scenario would have difficulty to explain the observed simultaneity of HXR emission in conjugate loop footpoints, which were found to be coincident within \( \lesssim 0.1\text{ s} \) (Sakao 1994; Kosugi 1996), but are separated by considerably larger electron travel times of 0.5-1.0 s.

Therefore, it seems that all proton models face some fundamental difficulties to reconcile the observed timing delays of impulsive HXR emission.

3. Particle Trapping Times

The bulk of HXR emission (\( \approx 50 - 90\% \), depending on the modulation depth of HXR pulses) is contained in smooth, slowly-varying time structures, which moreover exhibit an opposite sign of the energy-dependent time delay, compared with the fast-fluctuating HXR pulses (Aschwanden et al. 1996b; 1996c). The timing delays of this smooth HXR component was therefore interpreted in terms of particle trapping or energy loss inside the flare loop. This interpretation is mainly motivated by two reasons: (1) trapping is expected to smear out rapid fluctuations of the acceleration and injection process, and (2) the collisional deflection time or collisional energy loss time shows a functional dependence \( \tau \propto E^{3/2} \) that reproduces the correct sign and fits the functional form of the observed delay \( \tau(E) \) (see example in Fig. 1, bottom left).

Let us consider the collisional deflection time, which in any case should represent an upper limit of the particle trapping time in a flare loop. The collisional deflection time is defined by (e.g. Benz 1993),

\[
\tau_{\text{defl}}(E) := \frac{\mu^2}{\Delta v^2_\perp / \Delta t} = 9.5 \cdot 10^7 \frac{E_{\text{keV}}}{n_e} \left( \frac{m_T}{m_e} \right)^2 \frac{1}{Z_T^{2.1}} \frac{20}{\ln \Lambda} \text{[s]} \quad (5)
\]
with $E_{keV}$ the kinetic energy, $m_T$ the rest mass, and $Z_T$ the charge of the test particles, $n_e$ the electron density of the ambient plasma, and $\ln \Lambda$ the Coulomb logarithm. If we employ 50 – 100 keV electrons (to produce 25 – 50 keV HXR photons), the expected deflection time is about $t_{\text{defl}} \approx 0.3 – 1.0 \text{ s}$ in a flare loop with a typical electron density of $n_e \approx 10^{11} \text{ cm}^{-3}$. Considering the fit of $t_{\text{defl}}(E)$ to the observed time delay for the flare shown in Fig.1 (bottom left), we find that the smooth HXR flux has timing delays that are consistent with a trapping model in terms of collisional deflection. If we employ protons, the collisional deflection times would be a factor of $(E_p/E_e)^{3/2}(m_p/m_e)^2 \approx 10^9 – 10^{11}$ longer than for electrons, which is far beyond any delay ever measured in HXRs or gamma rays. The collisional deflection time, though an upper limit, is therefore no reasonable estimator of trapping times for protons. Pitch-angle scattering by strong wave turbulence or cross-field diffusion times in twisted magnetic flux tubes are believed to restrict the trapping times of ions or protons in flare loops to time scales of $\approx 10^2 – 10^4 \text{ s}$ (Ramaty & Mandzhavidze 1994), which are a factor of $\approx 10 – 10^3$ longer than collisional deflection times of electrons ($t_{\text{defl}} \approx 1 – 10 \text{ s}$ in typical flare loop densities; Aschwanden et al. 1996a; 1996b).

If we employ protons to generate the $\geq 25 \text{ keV}$ HXR emission (e.g. Simnett & Haines 1990), the precipitating protons are necessarily required to have an identical timing as the observed HXRs. This requirement for the proton timing cannot be reconciled with the observed timing delays of the smooth HXR flux for the following reasons: (1) If the smooth HXR flux would be produced by directly precipitating protons, the proton timing would have an opposite sign because of time-of-flight differences; (2) If the smooth HXR flux would be produced by initially trapped and subsequently precipitating protons, the proton trapping times would be much longer (a factor of $\approx 10 – 10^3$) than the observed HXR delays, which were found to fit electron collisional deflection times (Fig.1, bottom left). In the latter case, it would also be very difficult to understand that the trapping times of $> 1 \text{ MeV}$ protons would have exactly the same energy-dependence as the collisional deflection time of $\geq 20 \text{ keV}$ electrons (see Fig.1, bottom left). Thus, we see no suitable possibility to adjust the proton timing to the observed HXR delays, neither in terms of time-of-flight differences nor in terms of trapping time differences.

### 4. Conclusions

From previous work we found that the energy-dependent timing delays $\tau(E)$ of solar flare HXR emission in the energy range of $\approx 20 – 200 \text{ keV}$ are consistent with two timing processes: (1) the timing delays of the pulsed HXR flux are consistent with electron time-of-flight differences over spatial scales that correspond roughly to half a loop length, and (2) the timing delays of the smooth HXR flux are consistent with collisional deflection times for electrons in typical flare loop densities ($n_e \approx 10^{11} \text{ cm}^{-3}$).

In an attempt to explain the same timing results of HXR pulses in terms of protons, we considered two energy ranges, which both face fundamental difficulties: (1) $\approx 40 \text{ MeV}$ protons would match the same velocities and time-of-flight differences, but would require a proton flux far in excess of gamma-ray line observations, and (2) $\leq 1 \text{ MeV}$ protons have a velocity $\approx 10$ times smaller than 20 keV electrons and can only satisfy the observed time-of-flight differences for flight distances $\approx 10$ times smaller, which are difficult to reconcile with the observed simultaneity of conjugate HXR footpoint emission.

Employing protons to explain the observed timing delays of the smooth HXR flux would require that the trapping times of protons have the same energy dependence as collisional deflection times for electrons. This conflicts with estimates of proton trapping times, which are significantly longer than those of electrons, in the case of collisional deflection as well as for pitch-angle scattering by wave turbulence.
Based on these timing arguments it appears to be very unlikely that protons are responsible for producing $\geq 20$ keV HXR bremsstrahlung, e.g. as proposed by Simnett & Haines (1990). However, these timing results do not exclude that an arbitrary amount of ions (or protons) are accelerated concomitantly with electrons and propagate to the chromosphere, as evidenced by the observed nuclear gamma-ray lines (at 1-10 MeV) in large flares. The main conclusion of this study is that protons cannot be responsible for $\geq 20$ keV HXR emission, because their timing would be inconsistent with the observed HXR delays.

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Fig. 1.— The energy-dependent time delays $\tau(E) = t(40 \text{ keV}) - t(E)$ are shown for a flare observed on 1991 Dec 15, separately measured for the pulsed HXR flux (crosses on right-hand side) and the smooth HXR flux (diamonds on left-hand side), in the energy range of 40-300 keV. The delays can be fitted with two models: in terms of electron time-of-flight (TOF) differences (thick line on right-hand side bottom), and in terms of electron collisional deflection time differences (thick line on left-hand side bottom). The electron energies ($E \approx 2\varepsilon$) with the same timing delays as the HXR pulses (observed at energy $\varepsilon$) are indicated with thin lines (bottom part). For comparison, we show also the required timing of $>1 \text{ MeV}$ protons (left-hand side middle) and $>40 \text{ MeV}$ protons (left-hand side top), if they would be responsible for the $>20 \text{ keV}$ HXR emission. The trapping time of $>1 \text{ MeV}$ protons (dashed line on left-hand side middle) or $>40 \text{ MeV}$ protons (dashed line on left-hand side top) are so large (estimated with Eqn.6) that no energy-dependence can be seen on the displayed time scale of 1 s.