PARTICLE ACCELERATION AND KINEMATICS IN SOLAR FLARES AND THE SOLAR CORONA

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ABSTRACT

We review theoretical models of particle acceleration applied to solar flares (DC electric fields, wave-turbulence stochastic acceleration, shock acceleration) and confront these models with new observational findings from the Compton Gamma Ray Observatory (CGRO), Solar Maximum Mission (SMM), Yohkoh, and radio observations. Remote sensing of energetic particles via hard X-ray bremsstrahlung, gyrosynchrotron emission, and beam-driven plasma emission requires a self-consistent modeling of the particle kinematics in the solar flare plasma, including acceleration, injection, propagation, trapping, and energy loss of the particles. New insights in these kinematic processes have been obtained, besides modeling of energetic particle spectra, increasingly from sub-second timing studies, e.g. in the context of Masuda's discovery of above-the-loop-top hard X-ray sources, from electron time-of-flight delay measurements, from the relative timing of propagation to magnetically conjugate footpoints, from the relative timing of particle signatures in interacting flare loops with quadrupolar geometry, and from the relative timing of gyrosynchrotron emission and hard X-ray signatures in magnetic traps. We anticipate significant progress to be made with the High Energy Solar Spectroscopic Imager (HESSI), to be launched in 2000.

Key words: particle acceleration, kinematics, solar flares

1. INTRODUCTION

The investigation of particle acceleration and kinematics in solar flares still represents a difficult challenge, partially due to observational limitations (spatial and temporal resolution of current instruments), but partially also due to methodical problems in data analysis, which require a deconvolution of particle kinematics and radiation processes. Our diagnostic tools of solar nonthermal particles exploit chiefly information from collisional bremsstrahlung in hard X-rays (HXR), as well as from radio emission produced by electron beams, loss-cone instabilities, and gyro-synchrotron emission.

![Conceptual breakdown of the flare kinematics](image)

**Figure 1.** Conceptual breakdown of the flare kinematics into five different physical processes. This review is organized in order of these five steps.

In this review we organize the physics of particle kinematics in solar flares into five conceptual processes, which are believed to occur in sequential order during solar flares according to the simplest scenarios, but may also occur simultaneously in more convolved scenarios: particle acceleration (Section 2), particle injection (Section 3), particle propagation (Section 4), particle trapping (Section 5), and energy loss (Section 6). This concept is visualized in Fig.1.
2. PARTICLE ACCELERATION

It became customary to classify particle acceleration processes that are believed to operate in solar flares into three major groups: (1) DC electric field acceleration, (2) stochastic acceleration by gyro-resonant wave-particle interactions, and (3) shock acceleration. A recent review that along these lines can be found in Miller et al. (1997). (See also Kliem 1999 in this Proc.)

Let us first summarize the observational constraints that every theoretical model of a particle acceleration mechanism in a solar flare has to fulfill: (1) Total flare energies up to $10^{32}-10^{33}$ erg for $> 25$ keV electrons, and up to $10^{30}-10^{33}$ erg for $> 1$ MeV protons, (2) electron energies up to $100$ MeV and proton energies up to $1$ GeV, (3) production rates up to $10^{37}$/s for $>25$ keV electrons and $10^{35}$/s for $>1$ MeV protons, (4) flare durations of $\approx 10^2$ s, (5) acceleration times of $0.1-1$ s for $>25$ keV electrons and $1-2$ s for $>1$ MeV protons, (6) enhanced abundances of particle compositions, i.e. a factor of $\approx 3-10$ above the coronal value for Mg, Si, S, Ca, Ne, a factor of $10-20$ for Fe, and a factor of $\approx 2000$ for He$^3$/He$^4$, and (7) energy spectra with the form of broken power-laws, which probably require more than one single acceleration mechanism.

2.1. DC Electric Field Acceleration

Large-scale quasi-static electric fields represent conceptually the simplest mechanism to accelerate charged particles, and thus have been studied in some detail in applications to solar flares. Besides the force of the electric field $\mathbf{E}$, particles experience also a Coulomb drag force from the other charged particles in the distribution, so that the relative strength of the two forces is decisive whether a particle can be accelerated out of the bulk distribution. The drag force is maximum at the thermal speed. A critical field value is the Dreicer field $E_D = (e/4\pi\varepsilon_0)(\omega_{pe}/\nu_{th})^{1/2}$ V m$^{-1}$ (Dreicer, 1960), where the drag force at the thermal speed $v_{th}$ equals the electric field force. Electrons in sub-Dreicer fields ($\mathbf{E} < \mathbf{E}_D$) can be freely accelerated out of the bulk plasma, which is called runaway regime.

Acceleration models in sub-Dreicer electric fields have been proposed by Holman (1985) and Tsuneta (1985). Electric fields of order $\mathbf{E} \approx 10^{-5}$ V cm$^{-1}$ are thought to exist over the length of flare loops, $l \approx 30,000$ km, which can accelerate electrons up to energies of $10-100$ keV. The electric field has to be co-aligned with the magnetic field ($\mathbf{E} \parallel \mathbf{B}$), or can be oriented along a zero-field region, e.g. in a current sheet ($\mathbf{B} = 0$), in order to avoid disruptive $\mathbf{E} \times \mathbf{B}$ drifts during acceleration. Furthermore, to avoid prohibitive return currents, the electric fields have to be highly filamented. Holman (1985) proposed a configuration of $\approx 10^4$ oppositely-directed current channels to solve this dilemma. Tsuneta (1995) proposed recently a modified model where the field-aligned currents are located in the vortices of reconnection outflows. Although runaway acceleration in sub-Dreicer fields can explain bulk acceleration of electrons up to $<100$ keV (Holman & Benka 1992), this model faces serious difficulties to explain ion and electron acceleration to gamma-ray energies of 1-100 MeV. Additional problems are the pre-flare generation of electric fields, the stability of hyper-filamented current channels, fast (sub-second) modulation of electron pulses (seen in HXR) which are much faster than electric induction times, and electron kinematic timing constraints.

Acceleration models with super-Dreicer electric fields have been proposed, in the most recent version, by Litvinenko (1996). This model invokes a current sheet with a strong magnetic field $\mathbf{B}$, which magnetizes electrons during acceleration via a perpendicular super-Dreicer electric field $\mathbf{E} = \mathbf{v} \times \mathbf{B}$, set up by the lateral inflow $\mathbf{v}$ during steady-state reconnection. This model can explain electron energies up to $<100$ keV, but higher energies cannot be gained because electrons are scattered out of the current sheet via an $\mathbf{E} \times \mathbf{B}$ drift before they reach the end of the electric potential drop. This model has similarity with the Earth’s magnetotail and represents a promising candidate for bulk acceleration in flare reconnection models.

2.2. Stochastic acceleration

Stochastic acceleration defines a statistical process where particles gain or lose energy on short time intervals (like a diffusion process), but gain energy in the long-time average. The energy gain occurs via wave-particle interactions, which obey the Doppler resonance condition

$$\omega - \frac{\Omega}{\gamma} - \mathbf{k} \cdot \mathbf{v} = 0,$$

specified by the frequency $\omega$ and wave vector $\mathbf{k}$ of the waves on one hand, and by the velocity $\mathbf{v}$ (or Lorentz factor $\gamma = 1/\sqrt{1 - (v/c)^2}$) and gyrofrequency $\Omega$ (with harmonic number $s$) of the particle on the other hand. The process depends on the wave turbulence level $N(k)$, the particle velocity distribution $N(v, \alpha)$, and the dispersion relation $\omega(k)$ of the resonant waves. In the case of $s = 0$, the resonance is also called Landau or Cerenkov resonance. For integer values of the harmonic number $s$, the particle’s cyclotron frequency matches the Doppler-shifted wave frequency in the particle’s guiding center frame, and acceleration is thus tuned to highest efficiency like in a betatron accelerator. Generally, however, the wave frequency is not exactly tuned to the gyrofrequency of the particle, and thus stochastic kicks of energy gain and loss occur in the velocity phase space of the particles. From the dispersion relations of waves one can see that low-frequency waves with frequencies below the ion gyrofrequency ($\omega < \Omega_i$), i.e. ion sound waves, are efficient to accelerate ions, while waves with frequencies below the electron gyrofrequency ($\omega < \Omega_e$), i.e. whistler waves, are most efficient for electron acceleration. High-frequency waves above the gyrofrequency of electrons ($\omega > \Omega_e$), i.e. Langmuir waves, upper hybrid waves, electromagnetic O and X waves, are considered to be less efficient for acceleration of electrons, but may accelerate a small fraction of the velocity distribution tail that is sufficient to explain radio bursts. Obviously, a broadband wave spectrum
$N(k)$ is required to accelerate a particle out of the bulk distribution to high energies. The existence of an initial broadband wave spectrum $N(k)$ has generally been justified by the postulate of an MHD-turbulent cascade, which generates from the present long-wavelength Alfvén waves a continuous spectrum of shorter wavelengths. The broadband characteristic of the wave spectrum $N(k)$ has the powerful property that particles over a wide range of velocities can be accelerated, including electrons, protons, and ions such as Ne, Mg, Si, Fe. Stochastic acceleration can therefore nicely explain the enhancements of elemental abundances in flares. Stochastic acceleration by cascading of fast mode waves has been numerically simulated for protons and ions (Miller 1991, Miller & Viñas 1993, Miller & Roberts 1995, Miller, LaRosa & Moore 1996) and for electrons (Miller 1997). Stochastic acceleration seems to account for all observed requirements of hard X-ray and gamma-rays in solar flares, but may possibly require an initial bulk seed acceleration mechanism for the superthermal tail distribution. Observationally, however, we have no direct diagnostic of the wave turbulence level and wave spectrum in solar flares, which would permit quantitative tests of the stochastic acceleration model.


2.3. Shock acceleration

Shock acceleration is believed to be an established mechanism of particle acceleration for flare-related phenomena such as coronal mass ejections and radio type II bursts (herring-bone structure), which occur in the upper corona and interplanetary space, (see also related contributions in this Proc., Leblanc et al. 1999, Klein 1999). For flare-related particle acceleration in the lower corona, after the many Yohkoh observations of magnetic reconnection signatures in flares, more attention is recently paid to fast shocks in reconnection outflows, which could play an essential role for particle acceleration. We mention here just two newer models in this respect.

Somov & Kosugi (1997) proposed a model with a high-temperature turbulent-current sheet in the X-point reconnection site above the flare loop, where electrons and ions are trapped and experience first-order Fermi acceleration during their bouncing between the current sheet and the oblique collisionless shock propagating downward to the soft X-ray loop top. This model explains also the origin of above-the-loop-top HXR emission as observed by Masuda et al. (1994). For more details of this model see other contributions by Somov et al. (1999) in this Proc.

Tsuneta & Naito (1998) proposed a similar model with particle acceleration in the fast shock of the reconnection outflow downward from the X-point reconnection site. The highly oblique fast shock sandwiched by the slow shocks is considered as an ideal site for electron acceleration with the first-order shock Fermi mechanism. This scenario is also consistent with the coincident appearance of above-the-loop-top HXR sources as discovered by Masuda et al. (1994).

3. PARTICLE INJECTION

Particle acceleration is generally confined to a limited region where conditions for energy gain are favorable, e.g., a location with a potential drop of the electric field, a wave turbulence region, or a shock front. Particles may leave the acceleration site either directly (after the transit time through an electric potential drop or a shock front), or they may leave the acceleration in a diffusive manner (e.g., in the case of stochastic acceleration or diffusive shock acceleration). In the former case (of direct injection), time structures of the acceleration rate $N_{\text{acc}}(t)$ are preserved during subsequent propagation, permitting a combined kinematic model of particle acceleration and propagation. In the latter case (of diffusive injection), the acceleration rate $N_{\text{acc}}(t)$ of particles is convolved with the diffusion rate $N_{\text{diff}}(t)$, which can moreover be modulated by physical parameters that control the diffusion out of the acceleration region, e.g., magnetic field variations $B(t)$ in the case of a trapping field. The details of injection mechanisms (out of the accelerator) are little explored in the context of solar flares. In this review we focus on four observational findings that seem to be immediately related to the injection mechanisms: (1) bi-directional electron beams, (2) pulsed time structures, (3) spatio-temporal correlations of pulsed time structures, and (4) spatial fragmentation.

![Image of schematic model](image-url)

Figure 2. Schematic model of bi-directional (upward/downward) injection of electron beams from a coronal acceleration source, responsible for radio type III+RS burst pairs and correlated radio+HXR pulses.
3.1. Bi-Directional Electron Beams

An interesting property that permits some conclusions on the symmetry of the acceleration region is the observational finding of bi-directional radio burst pairs. Because the frequency-time drift rate $du/dt$ clearly allows to distinguish an upward propagating type III burst from a downward propagating reverse-slope (type RS) drift burst (assuming a monotonous decrease of the electron density with height), the observation of a simultaneous start of such a burst pair (III+RS) indicates bi-directional injection into opposite directions (Fig. 2). Such bi-directional beams have been observed also in conjunction with coincident HXR pulses (Aschwanden et al. 1993, Aschwanden et al. 1995b), which constitute a tri-fold detection of simultaneously-starting electron beams. Theoretical work on the production of bi-directional electron beams is in progress (Robinson & Benz 1999). The discovery of bi-directional electron beams can be considered, like the discovery of bi-directional EUV jets (Innes et al. 1997), as an indication of oppositely-directed ejections from a current sheet, with some spatial symmetry as provided in the case of X-type magnetic reconnection.

3.2. Pulsed Injection

The dynamics of particle acceleration and injection (onto coronal field lines) is one of the least understood aspects of solar flares. Steady magnetic reconnection (of Petschek or Sonnerup type) is thought to be driven by a steady lateral inflow that supplies steady bi-directional Alfvénic outflows along the current sheet axis. This process should also lead to a steady rate of particle acceleration, or at least to slowly-varying changes on time scales of Alfvénic transit times. However, HXR emission from flares exhibit fast (sub-second) time structures in at least 70% of the flares (Aschwanden et al. 1995a), while radio bursts on time scales of 0.1-1 s are observed in virtually all flares. Therefore, some highly dynamic processes must mediate either the magnetic reconnection itself, the related particle acceleration, or injection. There are only very few analytical models or numerical simulations on the "fast" dynamics of magnetic reconnection processes. Karpen et al. (1998) performed numerical simulations of shear-driven reconnection which produces magnetic islands that bubble out of the X-type reconnection point in time intervals of seconds. Kliem (1994) simulates the meander-like particle orbits around magnetic O-points and X-points, which exhibit a complicated diffusive injection process out of the trapping region of filamentary current sheets. Sakai & Ohasha (1987) study the oscillatory dynamics of coalescing current-carrying loops and reproduce relaxational oscillations between the magnetic collapse (driven by the $j \times B$ term) and the pressure gradient ($\nabla P$) in the current sheet.

Sometimes, radio bursts during flares exhibit periodic or near-periodic oscillation behavior (e.g. Rosenberg 1970, Aschwanden 1987, Aschwanden et al. 1994). In the case of such regular pulsations, some phase-locking with MHD oscillations of coronal loops seems to occur. However, strictly periodic pulses have never been observed in HXR. The general lack of strict periodicities indicates that the oscillatory dynamics of current sheets is highly nonlinear, producing intermittent sequences of more or less coherent electron injections. The picture is further blurred by the unknown degree of spatial fragmentation of the energy release region, which may consist of a large number of neighbored current sheets.

![Figure 3. Spatio-Temporal correlation between the minimum time scale $T_{\text{min}}$ of HXR time structures and the flare loop radius $r$ for a subset of 46 flares observed with Compton CGRO and Yohkoh (adapted from Aschwanden et al. 1999).](image)

### 3.3. Spatio-Temporal Correlations

A new clue on the interpretation of the fastest time structures in flares comes from studies that investigate correlations between time structures of HXR pulses and the spatial sizes of the connected flare loops. Employing a wavelet analysis, the distribution of time scales in $> 20$ keV HXR time profiles was studied for 46 flares (Aschwanden et al. 1998). The minimum time scale $T_{\text{min}}$ (varying in a range of 0.1-1 s) of the HXR time structures was found to correlate with the flare loop radius $r$, which can be characterized with a linear relationship (Fig. 3),

$$T_{\text{min}} = 0.5 \left( \frac{r}{10^6 \text{cm}} \right) \text{[s]} .$$

If we interpret the minimum time scale as an Alfvénic propagation time $T_{\text{min}} = l/v_A$ across a dynamic structure with length $l$, we obtain a scale-invariant size ratio $q = l/r$ for a given Alfvén velocity,

$$q = \frac{l}{r} = 0.034 \left( \frac{B}{100 \text{G}} \right) \left( \frac{n_e}{10^{11} \text{cm}^{-3}} \right)^{-1/2} .$$

In typical flare loops ($B \approx 100$ G, $n_e \approx 10^{11}$ cm$^{-3}$) the Alfvén velocity is $v_A \approx 700$ km s$^{-1}$. The size ratio $q$ of these dynamic structures amounts then to about 3.4% of the flare loop radius, i.e. 100-1000 km for typical flare loop sizes ($r = 3000 - 30,000$ km). It is conceivable that these dynamic spatial structures are associated with current sheets or turbulent MHD vortices.
4. PARTICLE PROPAGATION

We consider now the propagation of accelerated particles in the solar corona, after they have been energized to nonthermal energies and have left the acceleration region by some ejection or injection mechanism. The coronal plasma can be considered as collisionless for electron energies of \( \gtrsim 20 \text{ keV} \), so that they propagate as free-streaming particles along the magnetic field lines. The single particle orbits can be described by their gyromotion around the guiding center and the first adiabatic moment,

\[
\mu = \frac{\frac{1}{2} mv_\perp^2(s)}{B(s)},
\]

along a field line coordinate \( s \) with magnetic field \( B(s) \). The pitch angle \( \alpha(s) \) changes in response to the local magnetic field \( B(s) \),

\[
\cos \alpha(s) = \frac{v_\parallel}{v} = \sqrt{1 - \frac{2\mu}{mv^2} B(s)}.
\]

The propagation time from a coronal acceleration site to a chromospheric footpoint requires therefore the knowledge of the particle velocity \( v \), the initial pitch angle \( \alpha(s = 0) \), and the magnetic field \( B(s) \). A critical parameter is the magnetic mirror ratio \( R \),

\[
R = \frac{B(s)}{B(s = 0)}
\]

between the acceleration site \( (s = 0) \) and the chromospheric footpoint at location \( s \), which determines the loss-cone angle \( \alpha_0 \),

\[
\alpha_0 = \arcsin\left(\sqrt{\frac{1}{R}}\right)
\]

Particles with initial pitch angles that are smaller than the loss-cone angle, i.e. \( \alpha(s = 0) < \alpha_0 \), will precipitate directly to the chromospheric footpoints and lose their energy there by collisional bremsstrahlung. On the other side, particles with initial pitch angles that are larger than the loss-cone angle, i.e. \( \alpha(s = 0) > \alpha_0 \), will be mirrored and remain trapped in the coronal magnetic field of the flare loop. In the following Section we concentrate on the directly-precipitating electrons, while the kinematics of trapped electrons is described in Section 5.

4.1. Electron time-of-flight measurements

The Compton Gamma Ray Observatory (CGRO) provided a breakthrough in the analysis of electron kinematics in solar flares due to the high sensitivity and time resolution of the Burst and Transient Source Experiment (BATSE) detectors. By measuring the energy-dependent time delays \( \Delta t(\varepsilon) \) of HXR emission it was possible to measure the differential velocity dispersion of electrons that arrive in the chromospheric thick-target HXR emission site. From the kinetic energy \( E \) of a relativistic electron

\[
E = m_e c^2 (\gamma - 1)
\]
and the Lorentz factor $\gamma = 1/\sqrt{1 - \beta^2}$ one can express the relativistic velocity $\beta = v/c$ as function of the electron energy $E$.

$$\beta(E) = \sqrt{1 - \left[1 + \frac{E}{m_ec^2}\right]^{-2}}.$$  \hfill (9)

Two electrons with energies $E_1$ and $E_2$ have then a time-of-flight difference over a distance $l$,

$$\Delta t_{TOF} = \frac{l}{c \cos \alpha} \left[\frac{1}{\beta(E_1)} - \frac{1}{\beta(E_2)}\right].$$  \hfill (10)

The HXR bremsstrahlung photon spectrum $f(\varepsilon)$ can be calculated from an electron injection spectrum $f(E)$ via the Bethe-Heitler cross section (Brown 1971). A time-dependent electron injection spectrum $f(E,t)$ can be related to the time-dependent photon spectrum $f(\varepsilon,t)$ by a photo-to-electron energy conversion factor $q_E$.

$$q_E(\varepsilon, \gamma, E_0) = \frac{E(t)}{\varepsilon(t)}$$  \hfill (11)

that slightly depends on the spectral parameters $(\varepsilon, \gamma, E_0)$, but has a value that is close to $q_E \approx 2$ for most of the flares (Aschwanden & Schwartz 1996a).

This way, the electron energy $E = q_E \varepsilon$ can be substituted by the HXR photon energy $\varepsilon$ in Eq.9, and the time-of-flight distance can directly be determined from energy-dependent HXR time delays. An example of such a measurement is shown in Fig.5.

![Figure 5. Fitting of the time-of-flight model to energy-dependent HXR time delays $\Delta t(\varepsilon)$ in the energy range of 46-342 keV (right axis). The corresponding electron energies have a range of $\approx 100 - 700$ keV, or relativistic speeds of $\beta = 0.5 - 0.9$. The best-fit time-of-flight distance is $l = 20,000 \pm 1,800$ km. [Adapted from Aschwanden 1996].](image)

The time-of-flight distance $l$ obtained from HXR time delays is a measurement of the actual length of the helical trajectory along which a particle propagates. This projected length of this helical path is shorter by a factor $q_A = \cos(\alpha)$ that depends on the average pitch angle $\alpha$, and by a factor $q_H$ that depends on the twist angle of the magnetic field line. Assuming an isotropic pitch-angle distribution at the particle acceleration site and field line twisting below the kink-instability threshold, the factors are estimated to be $q_A \approx 0.64$ and $q_H \approx 0.85$, resulting in an overall correction factor of $q_A \times q_H \approx 0.54$ (Aschwanden et al. 1996a).

Applying these timing measurements to a comprehensive dataset of 42 flares simultaneously observed with CGRO and Yohkoh, a linear scaling law of $l_{TOF}/s = 1.4 \pm 0.3$ was discovered between the projected electron time-of-flight path $l_{TOF}$ and the flare loop half length $s = (\pi/2)r$ (Fig.6) (Aschwanden et al. 1996c).

4.2. Particle Acceleration Site

The localization of the particle acceleration site in flaring region is now constrained by three observational findings: (1) Above-the-loop-top HXR sources have been discovered by Masuda et al. (1994), which most likely indicate collisional energy loss of accelerated electrons in the trapping cusp region above the flare loop (Hudson & Ryan 1995, Fletcher & Martens 1998); (2) The near-simultaneity of conjugate HXR footpoint sources measured by Sakao (1994) places the acceleration site into a coronal position located about halfway between the loop footpoints; and (3) electron time-of-flight measurements by Aschwanden et al. (1996a,b,c) yield a scaling law of $l_{TOF}/s = 1.4 \pm 0.3$ between the projected electron time-of-flight distance $l_{TOF}$ and the SXR loop half length $s$, consistent with an acceleration site localized at about the double height of the primary HXR loop (Fig.7). Because the footpoint separation of the primary HXR flare loops amounts typically to 5000-50,000 km, the acceleration site is located in an altitude of $h_{acc} \approx 4000 - 40,000$ km.
4.3. Trajectories in Secondary Flare Loops

The scaling ratio $l_{TOF}/s = 1.4\pm0.3$ was found also to apply to interacting flare loop configurations, which consist of a compact primary flare loops with double HXR footpoint sources plus a secondary flare loop with an $\approx 3-4$ times larger size (Hanaoka 1997, Nishio et al. 1997). In such interacting flare loops in quadrupolar magnetic configurations, the acceleration site was found near the interaction point, located in a distance $l_{TOF}/s \approx 1.4$ above the primary flare loop. In some cases, additional time-of-flight measurements could be performed from the acceleration site to the remote footpoint of the secondary flare loop (Hanaoka et al. 1999), which were found to be consistent with time-of-flight distances of relativistic electrons. These observations confirm independently bi-directional electron injection, as it was concluded from radio type III+RS burst pairs (Section 3.1).
Figure 8. Two flares with double-loop interactions, shown in soft X-rays (grey-scale) and hard X-rays (thick contours). The four panels in each column contain the observed images (top row), images of the best-fit model (second row), and two views of the 3D-reconstructed quadrupolar loop configuration [from Aschwanden et al. 1999b].

The latter observations provide strong evidence for X-point magnetic reconnection in a quadrupolar geometry, with the particle acceleration site closely located near the reconnection point (or in reconnection outflows). Other position measurements of particle acceleration sites have also been inferred from radio images of type III and U bursts near their respective start frequencies, e.g., Kundu et al. (1995a,b), Raulin et al. (1995), Aurass & Klein (1997). However, because of incom-
Figure 9. Different electron trajectories as function of the initial pitch angle (left). Electrons with small initial pitch angles precipitate directly and their timing is given by the time-of-flight interval $t_{\text{TOF}} = I/\nu_0 \approx I \cdot E^{-1/2}$. Electrons with large initial pitch angles are intermittently trapped, until they become scattered into the loss-cone, later after a collisional deflection time, $t_{\text{coll}} \propto E^{3/2}/n_e$. The energy-dependent timing for the two processes is compared for a propagation distance of $l = 10^9$ cm and an electron density of $n_e = 10^{11}$ cm$^{-3}$ (right-hand panel).

Complete frequency coverage of current radio imaging instruments (e.g. VLA, Meudon, Nobeyama), as well as due to wave scattering properties of radio emission in the inhomogeneous corona (Bastian 1994; 1996), accurate position measurements of acceleration sites and propagating particle beams with respect to magnetic field geometries are difficult to achieve.

5. PARTICLE TRAPPING

Particle trapping in solar flare loops has been known since many decades (reviewed in chapter 8 of Benz 1993), based on observations of radio type IV sources and various decimetric radio bursts that have been interpreted in terms of loss-cone instabilities. Trapping in the magnetic mirror field of a dipolar flare loop is always expected, as long as there is a broad pitch-angle distribution and a mirror ratio larger than unity. Less known are the fractions of trapped particles, the efficiency of confinement, and the leakage rate. The escape rate from the trap has a lower limit by the Coulomb collision rate (weak-diffusion limit), while an upper limit is given by wave-resonant pitch-angle scattering (strong-diffusion limit). Recent measurements of energy-dependent HXR time delays have clarified these issues.

The rate of precipitating electrons $n(E, t)$ can be subdivided into two components: (1) a fraction $q_{\text{prec}}$ with small pitch angles ($\alpha < \alpha_0$) precipitates directly and has small time-of-flight delays, and (2) a fraction $(1 - q_{\text{prec}})$ with large initial pitch angles ($\alpha > \alpha_0$) is intermittently trapped and precipitates after some (energy-dependent) trapping delay:

$$n(E, t) = q_{\text{prec}} f(E, t) + (1 - q_{\text{prec}}) n_{\text{trap}}(E, t), \quad (12)$$

where the precipitation rate of trapped electrons, $n_{\text{trap}}(E, t)$, represents a convolution of the injection function $f(E, t)$ with the energy-dependent trapping time, $t_{\text{trap}}(E)$,

$$n_{\text{trap}}(E, t) = \frac{1}{t_{\text{trap}}(E)} \int_0^t f(E, t') \exp[-(t-t')/t_{\text{trap}}(E)] \, dt' \quad (13)$$

A deconvolution of 20-200 keV HXR data (Aschwanden 1997a,b, 1998a,b, 1999) has permitted a determination of energy-dependent trapping times, $t_{\text{trap}}(E)$, with the finding that the trapping time was consistent with the collisional deflection time,

$$t_{\text{trap}}(E) \approx t_{\text{coll}}(E) = 0.95 \cdot 10^8 \frac{(E \text{keV})^{3/2}}{n_e} \left( \frac{20}{\ln \Lambda} \right) \quad (14)$$

with electron densities ($n_e \approx 10^{11}$ cm$^{-3}$) that are typical for flare loops. Thus, trapping in the energy range of 20-100 keV seems to be governed in the weak-diffusion limit. Thus, HXR time profiles generally are composed of two energy-dependent time delays, which have oppositely-directed trends as function of energy: time-of-flight delays scale as $t_{\text{TOF}}(E) \propto l \cdot E^{-1/2}$, while trapping delays scale as $t_{\text{trap}}(E) \propto E^{3/2}/n_e$. Their energy-dependent behavior is shown in Fig.7 (right frame).

6. ENERGY LOSS

Based on the localization of the coronal acceleration and injection site in solar flares, the trajectories of nonthermal particles can be traced along magnetic field lines as outlined in simultaneous EUV, SXR and HXR images. Thanks to the density diagnostic of EUV and SXR images we are now in the position to calculate the mean free path length of propagating particles so that their energy loss sites can be accurately modeled. Electrons with energies $< 20$ keV generally suffer dominant energy loss in the coronal part of flare loops, while $> 20$ keV electrons lose...
their energy dominantly in chromospheric heights, in form of thick-target bremsstrahung HXR emission. In addition, Masuda’s discovery of above-the-loop-top HXR sources has demonstrated that coronal energy loss occurs also during the acceleration process, likely to be a consequence of efficient trapping in the acceleration region (see also review by Fletcher 1999 in this Proc.).

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