PARTICLE ACCELERATION IN IMPULSIVE SOLAR FLARES

II. Nonrelativistic Protons and Ions

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Abstract. Second-step acceleration of nonrelativistic protons and ions in impulsive solar flares is discussed extending our earlier calculations for relativistic electrons. We derive the relevant particle transport equation, discussing in detail the influence of the particle's effective charge and mass number on the various momentum gain (stochastic acceleration, diffusive shock wave acceleration) and loss (Coulomb interactions, particle escape) processes. Analytical solutions for the ion-momentum spectra in the hard-sphere approximation are given. The inclusion of Coulomb losses modify the particle spectra significantly at kinetic energies smaller than $E_p = 0.64(\theta_e/5.0)\text{ MeV nucl.}^{-1}$ from the well-known Bessel function variation in long-duration flares. For equal injection conditions this modification explains the observed much smaller ion fluxes from impulsive flares at high energies as compared to long-duration flares. We also calculate the $^{3}\text{He}^{4}\text{He}$-isotope variation as a function of momentum in impulsive flares in the hard-sphere approximation and find significant variations near $E_m = 0.38(T_e/2 \times 10^6\text{ K})\text{ MeV nucl.}^{-1}$, where $T_e$ is the electron temperature of the coronal medium.

1. Introduction

Recently, it has been demonstrated (Steinacker et al., 1988, hereinafter referred to as paper SDS) that the inclusion of Coulomb energy losses in the theoretical analysis of stochastic particle acceleration provides an excellent explanation of the observed spectral differences (Evenson et al., 1985) of relativistic electrons in long-duration and impulsive solar flares. The long-duration flares occur high enough in the solar corona that Coulomb losses are negligible, and exhibit the well-known power-law electron behaviour in momentum (Lin, Mewaldt, and Van Hollebeke, 1982). Alternatively, according to our explanation the impulsive flares occur much deeper in the corona so that due to the larger gas density the Coulomb loss time becomes shorter than the acceleration time. In this case a deviation from the power-law behaviour results at small momenta $p \lesssim \theta_e m_c c$ where the spectrum exhibits an exponential increase $\exp(\theta_e m_c c/p)$, whereas at large momenta $p \gtrsim \theta_e m_c c$ the distribution function approaches the same power law as obtained for long-duration flares. The measured electron spectrum of the impulsive flare from 14 August, 1982 is well reproduced with a value $\theta_e = 3$.

It is the purpose of this paper to study the influence of Coulomb energy losses in impulsive flares on energetic protons and ions in the acceleration process. Cane, McGuire, and von Rosenvinge (1986) have measured that impulsive flares have large electron-to-proton ratios $e(4-19\text{ MeV})/p(9-23\text{ MeV})$ ranging from 0.02 to greater than 10, as compared to long-duration flares where the ratio covers the range from 0.001 to 0.08. Of course, the best studied flares in the literature are those with high proton and ion fluxes, which according to the work of Cane, McGuire, and von Rosenvinge (1986)
are long-duration flares. And for those the well-known Bessel function behaviour of the
distribution function at nonrelativistic energies (Pikel'ner and Tsytovich, 1976; Barbosa,
1979; Ramaty, 1979; Dröge and Schlickeiser, 1986) has been clearly established for
different nuclei (for review see McGuire and von Rosenvinge, 1984). Here we are more
concerned with the proton-poor impulsive events where we expect in analogy to the
electron spectra – and as we shall demonstrate – strong deviations from the canonical
Bessel function behaviour. We are not aware of any systematic study of proton and ion
spectra in impulsive flares in the literature, but we have noticed that rather unusual
nucleon spectra have been reported during the 'prompt' solar event from 22 November,

2. Stochastic Acceleration of Energetic Protons and Ions in Solar Flares

Our physical model of particle acceleration in solar flares has been described in detail
in the first paper of this series (SDS): rapid bulk energization of thermal electrons due
to reconnection of magnetic field lines has generated shock waves and Alfvénic
turbulence which both accelerate nucleons and electrons above a certain threshold
energy to higher energies.

The behaviour of energetic particles of mass \( m = A m_p \) (\( m_p \): proton mass), effective
charge \( Q_{\text{eff}} = Z e \) and total momentum \( p_{\text{tot}} = A p \), where \( p \) denotes the momentum per
nucleon, in an ordered uniform magnetic field \( B_0 \) with superposed transverse Alfvén
waves propagating parallel and/or antiparallel to \( B_0 \) has been considered by Schlickeiser
(1989a, b), discussing in detail the influence of the wave's cross and magnetic helicity.
The magnetic field \( B_0 \) is embedded in a cold background medium which moves with bulk
speed \( U \) parallel to \( B_0 \). For equal intensity and zero magnetic helicity of parallel and
antiparallel propagating waves the collisionless Boltzmann equation for the differential
particle's phase space density can be reduced to a quasi-linear transport equation for
the isotropic part of the gyrophase-averaged phase space density \( F(z, p_{\text{tot}}, t) \) which
reads (Schlickeiser, 1989b; Kirk, Schlickeiser, and Schneider, 1988)

\[
\frac{\partial F}{\partial t} - \frac{1}{p_{\text{tot}}^2} \frac{\partial}{\partial p_{\text{tot}}} \left[ p_{\text{tot}}^2 D(p_{\text{tot}}) \frac{\partial F}{\partial p_{\text{tot}}} \right] - \frac{1}{p_{\text{tot}}^2} \frac{\partial}{\partial p_{\text{tot}}} \left[ \left( \frac{1}{3} \frac{dU}{dz} p_{\text{tot}} \right) \right. \\
\left. \left. - p_{\text{tot}} \right) \right] \right] = Q(z, p_{\text{tot}}, t),
\]

where \( 4 \pi p_{\text{tot}}^2 F(z, p_{\text{tot}}, t) \) is the number of particles per unit volume element and unit total
momentum element at spatial position \( z \) at time \( t \) with momentum \( p_{\text{tot}} \). \( Q(z, p_{\text{tot}}, t) \)
represents sources and sinks of particles and \( p_{\text{tot}} \) describes spontaneous momentum
losses of particles (here Coulomb and ionization losses).

The spatial \( (K) \) and momentum \( (D) \) diffusion coefficients both are related to the
particle's mean free path \( (l) \) against scatterings, which in turn depends on the statistical
properties of the Alfvénic turbulence. For a power-law spectrum of magnetic field