Proceedings of ICRC 2001: 3223

ICRC 2001

The relation between cyclotron heating and energetic particles on open coronal field lines

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Abstract. Cyclotron resonance with high-energy Alfvén waves has been proposed as an ion heating mechanism for producing high-speed winds and large ion temperatures in coronal holes. In the simplest model the waves propagate undisturbed until they are dissipated at a distance where the ion cyclotron frequency becomes comparable to the wave frequency. A more complex model includes the effects of nonlinear interactions that cascade the wave power from low to high frequencies.

The mean free path of energetic particles acts as an important parameter to particle acceleration and propagation in solar corona. Thus the fluctuation spectrum required by the heating models is directly coupled with high energy particle production.

In this report we present the energetic particle mean free path on open coronal field lines, resulting from the cyclotron heating model, and study its implications to particle acceleration. The constraints set for the heating models are discussed.

1 Introduction

The coronal mean free path of energetic particles is an important parameter for all particle acceleration models relevant on open coronal field lines (Vainio et al., 2000; Kocharov et al., 1999; Kobak and Ostrowski, 2000). For efficient acceleration, the scattering of particles provided by the magnetic field fluctuations must be strong enough to keep the particles in the acceleration region. Estimating the scale lengths of diffusion, acceleration region and ambient magnetic field one can determine a relation between mean free path and the typical attainable energy for various acceleration processes.

The MHD-turbulence in the inner heliosphere was extensively studied by the two Helios missions (see Marsch, 1991, for a review). The observed turbulence spectrum steepens near proton cyclotron frequency, indicating that dissipation by cyclotron resonance is an important phenomenon in the solar wind energetics. In addition, a spectral steepening from spectral power law index $q = 1$ to $q = 5/3$ at lower frequencies was observed. This observation would suggest that spectral evolution takes place in the solar wind.

Dissipation of waves in corona and interplanetary medium is one of the mechanisms proposed for heating the corona and accelerating the solar wind. McKenzie et al. (1995) showed that the high speed wind and hot ions observed in the coronal holes could result from the damping of high-frequency Alfvén waves by cyclotron-resonant plasma ions. The heating models assume the waves to originate either at the base of the corona (e.g. Tu and Marsch, 1997, and references therein) or throughout the corona, with non-linear cascading processes transferring power from low to high frequencies (e.g. Hu et al., 1999, and references therein).

In this study we present energetic particle mean free path on open coronal field lines. Our intention is to demonstrate the effect of coronal wave-heating models on the particle transport and acceleration on open coronal field lines. As an example, we consider an intermediate-speed solar wind stream with a single f^{-1} spectrum of outward-propagating Alfvén waves extending to a dissipation frequency near the local proton–cyclotron frequency. For simplicity, the cascading processes are not included. We employ the extended quasi-linear theory (EQLT) of Ng and Reames (1995) to calculate the mean free path at distances below 0.3 AU from the Sun. The result is discussed from the point of view of particle acceleration and transport, and reflected back to point out the constraints it sets on the coronal heating models.

2 The model

2.1 The waves and the coronal medium

We assume that the propagation of high-frequency Alfvén-waves from the solar surface up to the dissipation point is described by WKB theory. Thus, in a steady state for $f < f_{\rm H}(r)$, we get the power spectrum of the magnetic fluctua-

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tions, $P(f,r)$, from the conservation of the wave action,

$$P(f,r)M(r)[M(r)+1]^2 = P_0(f)M_0(M_0+1)^2, \qquad (1)$$

where $M(r) = V(r)/V_\mathrm{A}(r)$ is the Alfvénic Mach number of the radial flow, $V_\mathrm{A} = B_r/[4\pi m_\mathrm{p} n]^{1/2}$ is the radial component of the Alfvén speed, $n(r)$ is the electron density, $B_r(r)$ is the radial component of the magnetic field, m_p is the proton mass, and $X_0(f) \equiv X(f,r_0)$ denotes the reference value of parameter X at distance r_0. At the distance r, where the wave's (conserved) frequency hits the dissipation frequency the wave is absorbed by the plasma protons. We use the initial wave spectrum $P(f,R_\odot) = P_\odot/f$ with $P_\odot = 10^{-3}$ G^2 in agreement with low-frequency interplanetary observations.

The magnetic field is taken to be radial with coronal base value of 1.3 gauss. Density and proton thermal speed, $v_\mathrm{p} \equiv [2k_\mathrm{B}T_\mathrm{p}/m_\mathrm{p}]^{1/2}$ are obtained from the results of Tu and Marsch (1997) by approximate fitting (Vainio and Laitinen, 2001). The solar wind velocity profile is obtained from the conservation of nV/B_r provided by the equation of continuity, using a reference value of $V_0 = 550$ km s^{-1} at $r_0 = 65\,R_\odot$ by Tu and Marsch (1997).

2.2 Dissipation frequency

The cyclotron damping rate of Alfvén waves propagating parallel to the field lines is (e.g. Stix, 1962)

$$\gamma(f,r) = \Omega_\mathrm{p}\frac{\sqrt{\pi}}{2}\frac{f_\mathrm{p}}{\beta_\mathrm{p}^{1/2}f}\exp\left\{-\frac{f_\mathrm{p}^2}{\beta_\mathrm{p}f^2}\right\}, \qquad (2)$$

where $f_\mathrm{p} = \Omega_\mathrm{p}(M+1)/2\pi$ is the Doppler-shifted proton–cyclotron frequency, $\beta_\mathrm{p} = 8\pi n k_\mathrm{B}T_\mathrm{p}/B^2$ is the proton plasma beta, T_p is the proton temperature, and k_B is Boltzmann's constant. Assuming that the spectrum terminates at the frequency, where the damping length, $(V+V_\mathrm{A})/2\gamma$, equals the distance from the surface of the Sun, $r - R_\odot$, we get an equation

$$\Omega_\mathrm{p}\sqrt{\pi}\frac{f_\mathrm{p}}{\beta_\mathrm{p}^{1/2}f_\mathrm{H}}\exp\left\{-\frac{f_\mathrm{p}^2}{\beta_\mathrm{p}f_\mathrm{H}^2}\right\} = \frac{V+V_\mathrm{A}}{r-R_\odot}$$

that can be solved by iteration (Vainio and Laitinen, 2001). As no spectral evolution is applied, the termination frequency must decrease with distance. Further, we do not want to consider waves that are too much affected by dispersive effects, so we take $f_\mathrm{H}(r) \leftarrow \min\{f_\mathrm{H}(r), 0.5\,f_\mathrm{p}(r)\}$.

The exact way of taking cyclotron damping into account is to multiply the right hand side of Eq. (1) by

$$\exp\left\{-\int_{r_0}^{r}\mathrm{d}r'\frac{2\gamma(f,r')}{V(r')+V_\mathrm{A}(r')}\right\}.$$

Vainio and Laitinen (2001) have numerically integrated the damping decrement and found the approximation very reasonable.

2.3 Energetic-particle mean free path

Energetic-particle mean free path λ is related to the pitch-angle diffusion coefficient $D_{\mu\mu}$ by (e.g. Schlickeiser, 1989)

$$\lambda = \frac{3v}{8}\int_{-1}^{+1}\frac{(1-\mu^2)^2}{D_{\mu\mu}}\mathrm{d}\mu. \qquad (3)$$

The standard quasi-linear theory (SQLT) form of $D_{\mu\mu}$ due to a spectrum of parallel-propagating Alfvén-waves for super-Alfvénic ($v \gg V_\mathrm{A}$) protons is given by

$$D_{\mu\mu}^{\mathrm{SQLT}} = \frac{\pi}{2}\frac{\Omega^2}{B^2}(1-\mu^2)\frac{I(-\Omega/v\mu)}{|v\mu|},$$

where μ, v, and $\Omega = eB/(\gamma m_\mathrm{p}c)$ are the pitch-angle cosine, speed, and gyro-frequency of the particle (all measured in the wave frame). Here, $I(k)$ is the wavenumber spectrum of the Alfvén waves, where positive (negative) values of the wavenumber k denote left-handed (right-handed) helicity. It is evaluated in each point of velocity space at a single, resonant wavenumber $k = -\Omega/v\mu$.

In our model the spectrum has a termination wavenumber k_H, which in effect removes scattering for pitch angles $|\mu| < \mu_\mathrm{c} \equiv \Omega/(vk_\mathrm{H})$. In order to scatter to other hemisphere the particle needs thus other, non-resonant scattering processes. Several models for filling the resonance gap have been presented in literature. Resonance broadening due to finite wave–particle interaction times caused either by thermal damping (Schlickeiser and Achatz, 1993) or by turbulent spectral evolution (Bieber et al., 1994) would be one option. In the present model, however, turbulent spectral evolution is neglected, and thermal damping does not produce enough resonance broadening: it would require waves with large damping rates to be present in the spectrum but in our model, waves with damping rates larger than $(V+V_\mathrm{A})/(r-R_\odot)$ are absent. Adaptation of spectral index $q < 6$ above k_H would also remove the resonance gap (Vainio, 2000), provided that cyclotron waves propagating in both directions are present. However the model by Tu and Marsch (1997) doesn't follow these requirements.

In the extended quasi-linear theory of Ng and Reames (1995), one obtains resonance broadening by including (non-resonant) medium-scale fluctuations, $\Delta\boldsymbol{B}$, of the magnetic field to the equation of motion of particles, and then ensemble averaging the resulting forces over the gyro phase of the particles, as well as the gyro phase and magnitude of these fluctuations. This turns out to be a very efficient process, since effectively, the pitch-angle diffusion coefficient of SQLT gets smoothed with a function of half width $\sim b_\perp \equiv \Delta B/B$. In addition, a broadened Čerenkov resonance appears. We adopt this model of pitch angle scattering for our study. The detailed derivation of the pitch angle diffusion coefficient for our specific case is presented in Vainio and Laitinen (2001).

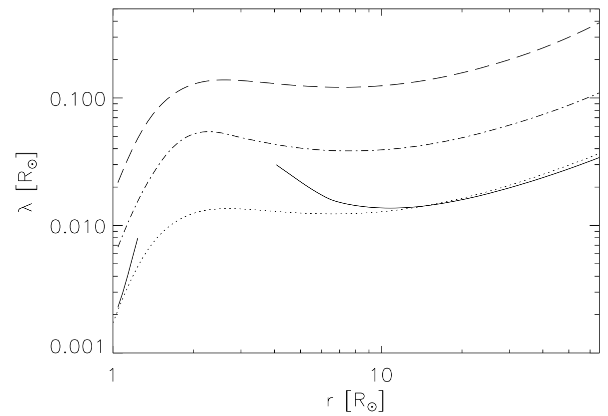

Fig. 1. The EQLT mean free path as a function of distance in solar corona for energies $E = 1$ (*solid curve*), 10 (*dash-dotted curve*), and 100 MeV (*dashed curve*). The resonant part of the 1-MeV mean free path is also shown (*dotted curve*) (Vainio and Laitinen, 2001).

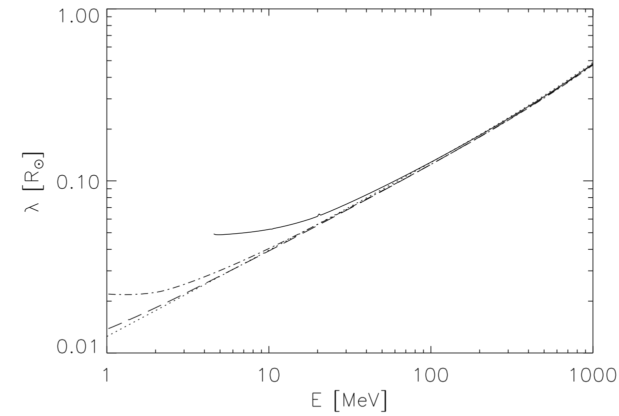

Fig. 2. The EQLT mean free path as a function of energy in solar corona for distances $r = 2$ (*solid curve*), 5 (*dash-dotted curve*), and 10 $R_\odot$ (*dashed curve*). The resonant part of the mean free path at 10 $R_\odot$ is also shown (*dotted curve*) (Vainio and Laitinen, 2001).

3 Results and discussion

The numerically calculated EQLT mean free path is presented in Figs. 1 and 2. The most prominent features visible are the shell of extremely small mean free path close to Sun and the second minimum at around $10\,R_\odot$. At lower energies, the curve is cut abruptly, which is a consequence of EQLT not being able to close the resonance gap at these energies. For higher energies the mean free path is almost constant from 2 to 10 $R_\odot$.

The characteristic attainable energy for shock acceleration can be estimated from $\kappa(v_\mathrm{c}, r)/u = v_\mathrm{c}\lambda(v_\mathrm{c}, r)/(3u) \sim r/2$ (Vainio et al., 2000), where κ is the diffusion coefficient, v_c the particle's characteristic velocity and u the shock upstream velocity. This is presented in Fig. 3 for a number of shock velocities. The shock is required to be super-Alfvénic, i.e. $u = V_s - V > V_A$.

A shell of strong acceleration is located close to the solar surface. This is consistent with observations of shock acceleration by metric type II burst associated shocks in many gradual solar energetic particle events. Also chromospheric and coronal Moreton waves have been associated with energetic particle production and injection, at a wide range of longitudes (Cliver et al., 1995; Torsti et al., 1999). If a shock or turbulent conditions favorable for stochastic acceleration is associated with the Moreton wave, energetic particles may be produced on low altitudes far from active regions.

The acceleration efficiency begins to rise again at few $R_\odot$, reaching maximum at few tens of $R_\odot$. The observed deceleration of the fastest CMEs at these distances (Sheeley et al., 1999) would move the maximum sunwards. It is however unclear whether this deceleration occurs in the head of the CME or rather in the flanks and rear (Sheeley et al., 2000). Particle acceleration at distances around 10 $R_\odot$ has been observed in gradual events (Kahler, 1993, 1994; Torsti et al., 1998; Anttila and Sahla, 2000).

Further away from the Sun the mean free path increases slowly but remains still rather small. Estimating the diffusion timescales with $\tau \approx r^2/(2v\lambda)$ with the maximum mean free path at 65 $R_\odot$ would produce diffusive time lag of several days for 10 MeV protons for traveling to 0.3 AU, inconsistent with the time lags observed in energetic particle events on low latitudes. For high latitudes, only few measurements of energetic particle events have been reported. In high velocity streams the low densities yield very high Alfvén speeds, thus only very fast CMEs would produce strong shocks for efficient particle acceleration. Bothmer et al. (1995) report observations of three events with delay times of several days in the high-speed region over the south pole by Ulysses spacecraft. Definite conclusions of the transport however cannot be made, as the spacecraft was far from the Sun during the events (near 3.5 AU).

Tu and Marsch (1997) discard the effect of cascading in their model, assuming that the cascade only starts above 10 $R_\odot$. On the other hand, Hu et al. (1999) include heating resulting from the cascade in their model, and find it to be very efficient already at low altitudes. Since the cascading steepens the turbulence spectrum and removes power to dissipation, a longer mean free path results, more consistent with the observed mean free path in the interplanetary space.

Marsch (1991) report that the spectral break point suggesting cascading moves to lower frequencies in slower solar winds. On high-speed polar winds, cascading is also present, although it evolves significantly slower (Horbury et al., 1996). Such a dependence between the solar wind speed and the cascade strength would result in longer mean free paths in slower solar winds. This can also be seen in particle events: impulsive events, associated with long mean free paths (e.g. Kahler, 1993), are usually observed on slower solar winds than gradual events (Slivka et al., 1984), which in turn have much smaller mean free paths.

Also the geometry of the turbulence affects the mean free

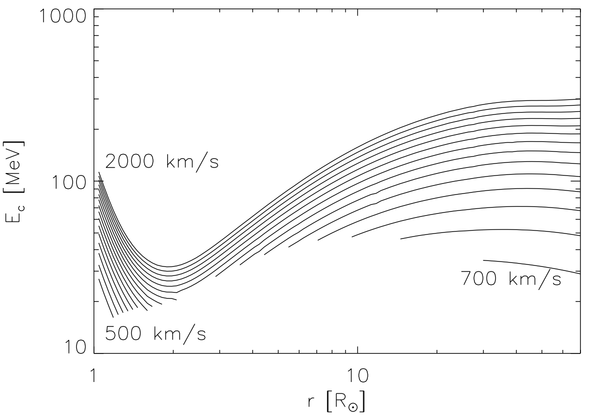

Fig. 3. The characteristic attainable energy for shock acceleration as a function of shock distance from the Sun, for shock velocities $V_s = 500 - 2000$ km/s with 100 km/s intervals.

path. According to the solar wind observations at 1 AU, most of the fluctuations have their wavevectors perpendicular to the magnetic field direction (Bieber et al., 1996). Such fluctuations do not scatter the particles resonantly, thus the mean free path in turn would be longer (Bieber et al., 1994). Leamon et al. (2000) suggest that a significant portion of the wave power is cascaded rapidly to high perpendicular wavenumbers and eventually to short scale non-cyclotron resonant dissipation processes. If this process operates fast enough, most of the wave power that would otherwise accelerate the solar wind in the interplanetary space, would be destroyed in low corona, and a slow solar wind with large mean free path, consistent with impulsive events, would result.

4 Conclusion

We have estimated the energetic particle mean free path in the solar corona following the assumptions of cyclotron heating model of Tu and Marsch (1997). The calculations suggest that, in addition to a short mean free path shell in the low corona, another minimum at around 10 $R_\odot$ exists. Estimating the efficiency of the shock acceleration, the second maximum of the characteristic attainable energy for a constant-velocity shock wave is around a few tens of $R_\odot$. Energetic particle observation of gradual events have shown consistent observations of particle acceleration below 2 $R_\odot$ and again at around 10 $R_\odot$ (Torsti et al., 1998; Anttila and Sahla, 2000).

Further away from the Sun the calculations yield too short mean free path. However, two processes not included in the current study may improve estimates there. Firstly, the used heating model of Tu and Marsch (1997) doesn't take into account turbulent cascading that transfers fluctuations to higher frequencies and hence to dissipation range, thus steepening the spectrum. Including this effect (Hu et al., 1999), would increase the mean free path in the region of the latter minimum, thus decreasing the acceleration efficiency there. Another effect that should be taken into account in further studies is the cascading of turbulence to perpendicular wave numbers, which would also increase the mean free path. The time and height scales of these processes are essential for the study of particle propagation and acceleration also in lower altitudes.

Acknowledgements. The authors wish to acknowledge helpful discussions with L. Kocharov.

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