ON THE STORAGE OF HIGH-ENERGY PROTONS IN
THE SOLAR CORONA: THE CYCLOTRON INSTABILITY

B. I. MEERSON and I. V. ROGACHEVSKII

Institute of Applied Geophysics, the USSR State Committee for Hydrometeorology and
Control of the Natural Environment,
20-B, Glebovskaya ul., Moscow, 107258, U.S.S.R.

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Abstract. We consider the problem of long-time storage of high-energy protons, accelerated in the process
of a flare, in coronal magnetic traps. From the viewpoint of the storage, one of the most important plasma
instabilities is the kinetic cyclotron instability of the Alfvén waves. We carry out a detailed theoretical
analysis of the instability for typical conditions of the solar corona. It is the refraction of the Alfvén waves
in combination with a drastic decrease of the instability growth rate with an increase of the angle between
the directions of the wave vector and the stationary magnetic field that leads to the possibility of the
long-term storage of the flare protons. Sufficient conditions of the storage are determined.

1. Introduction

High-energy protons, accelerated in the process of solar flare and injected into coronal
regions of closed magnetic fields, can be trapped by these magnetic configurations
(Figure 1). Subsequent evolution of the trapped protons (quick loss in the solar
atmosphere, long-time storage in the trap, or escape into interplanetary space?) is of
great interest.

Simple estimates show that Coulomb collisions in the coronal plasma (the concentra-
tions \(n_0\) we are interested in are of the order of \(10^7-10^8 \text{ cm}^{-3}\)) limit the lifetime of
the protons with energies more than 10 MeV to the time of the order of 1 day. Protons with these energies also take a day to escape, due to the magnetic drift in a non-uniform and curved magnetic field (the intensity $B_0 \approx 1-10$ G). However, there are processes which are able to reduce the life-time of the particles in such traps to some minutes. Meerson and Sasorov (1981) noted that if the energy density of flare-injected plasma (with allowance made for energetic particles) becomes comparable with, or greater than the pressure of the magnetic field, the magnetic configuration breaks down. It is the impossibility of combined ‘magnetic field-plasma’ equilibrium or MHD-instability of the equilibrium which cause the breakdown (Meerson and Sasorov, 1981). In this case, an appreciable amount of plasma together with energetic protons and frozen-in magnetic fields is ejected from the trap on a timescale of $\tau \approx L/c_A$, where $L$ is a characteristic size of the trap, $c_A = B_0(4\pi n_0 m_i)^{-1/2}$ is the Alfvén velocity, $m_i$ is the ion mass. For typical values of $L \approx 10^{10}$ cm and $c_A \approx 10^8$ cm s$^{-1}$ we have $\tau \approx 10^2$ s.

If the pressure of both background plasma, $p_0$, and high-energy protons, $p_h$, is much less than the pressure of the magnetic field, i.e., if

$$p_{0,h} \equiv 8\pi p_{0,h}/B_0^2 \ll 1,$$  (1.1)

the plasma in the trap can be stable with respect to fast large-scale MHD perturbations. In this case, however, various kinetic instabilities are essential. Some instabilities of this kind have already attracted attention. Meerson et al. (1978) investigated the bounce-resonant instability of the fast (magneto-acoustic) mode driven by high-energy protons with a peaked energy distribution. According to Meerson et al. (1978), this instability can support MHD-oscillations of a coronal condensation which give rise to a periodic modulation of type IV radio emission. Another example of kinetic instability driven by trapped high-energy protons was analyzed by Meerson and Sasorov (1981). They studied the gradient instability of the Alfvén waves due to the magnetic drift resonance with the protons.

However, it is the cyclotron instability (Sagdeev and Shafranov, 1960) that can be the most important in the situation considered. The instability arises due to anisotropy of longitudinal and transverse (with respect to the magnetic field) pressures of high-energy component of the plasma. In our case of a ‘magnetic mirror’ such anisotropy, namely, $p_{h\perp} > p_{h\parallel}$, is determined at least by a ‘loss-cone’ of the velocity distribution function of energetic protons. The cyclotron instability generates Alfvén waves by means of their resonant amplification by high-energy protons. If the plasma is homogeneous, the condition of cyclotron resonance takes the form

$$\omega - k\parallel v\parallel - n\omega_{B\parallel} = 0, \quad n = 0, \pm 1, \pm 2, \ldots,$$  (1.2)

where $\omega$ is the wave frequency, $\omega_{B\parallel}$ is the proton gyrofrequency, $v\parallel$ is the component of proton's velocity along the direction of the stationary magnetic field $B_0$, $k\parallel = k \cos \theta$, $k$ is the absolute value of the wave vector $k$, and $\theta$ is the angle between $k$ and $B_0$. The case of $n = 0$ in (1.2) corresponds to the Čerenkov resonance.

The scattering of high-energy protons by growing waves (Kennel and Petschek, 1966) can lead to a quick particle drift to the loss cone, i.e., to their precipitation into dense