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Signatures of Coronal Magnetic Field Geometry in Gamma-Rays, Neutrons, and High-Energy Protons

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Abstract

We consider how tilt and divergence of magnetic field lines in solar corona affect distribution functions of interacting and interplanetary protons. It is shown that signatures of magnetic field geometry may be found in anisotropy of secondary high-energy neutrons and γ-rays, in ratio of numbers of interplanetary to interacting protons, in proton energy spectra, in the characteristic decay times of γ-ray and neutron emissions, and in a spatial distribution of the secondary emission sources on solar disc.

1 Tilt of magnetic field lines:

In the solar cycle 22, observations of high-energy γ-ray and neutron flares suggest more isotropic production of high-energy neutral emissions than it was expected earlier (Mandzhavidze & Ramaty, 1993). One possible explanation of these observations is that the high-energy emissions are produced in complex magnetic structures with varying configurations from flare to flare (Chupp et al., 1993, Trottet et al., 1993).

Importance of strongly tilted magnetic fields at the flare site has been demonstrated by Kocharov et al. (1997). They started with analysis of magnetic structures at sites of two flares responsible for >100 MeV neutron events. Based on these observations, a model of neutron production was considered. The model takes into account the observed large tilt of magnetic field lines at footpoints of flare magnetic loops. Results of the new calculations have been compared with both previous calculations and observations. The tilt of magnetic field lines at the flare site is proved to be the most important parameter limiting anisotropy of high-energy secondary emission in solar flares. It can be concluded that: (1) The tilt of magnetic field lines at footpoints of flare loops is a key parameter for theoretical calculations of anisotropy of high-energy neutron and γ-ray emissions. This parameter was not taken into account in previous calculations. (2) Large magnetic tilt angles actually observed imply much more isotropic emission than that expected in earlier studies. (3) High-resolution magnetograms and stereoscopic observations of γ-ray and neutron emissions are desirable for a more accurate determination of parameters of accelerated ions at the Sun.

2 Divergence of closed magnetic field lines:

Possible divergence of magnetic field lines in coronal portion of a magnetic loop may affect trapping and acceleration of solar particles. Analytic steady-state solutions to the focused diffusion equation have been used to deduce proton trapping time, τ_{trap}, an average residence time for all particles injected in the magnetic loop (Kocharov et al. 1999a). We take into account effect of MHD turbulence and divergence of magnetic field lines in both corona and chromosphere of the Sun. The numerical simulations of pitch-angle scattering have been also used to check analytic solutions and to ascertain boundary conditions to the focused diffusion equation. Results have been obtained for several different functional forms of $B(\zeta)$, the magnetic field as a function of distance along a particular coronal field line. Five cases have been studied, from B being constant along the coronal portion of the loop to $B(\zeta)$ corresponding to a force-free magnetic structure. The results indicate that divergence of magnetic field in coronal portion of the loop can significantly increase the trapping time, no matter how small mean free path may be. Derived analytic expressions for τ_{trap} should be used for calculation of intensity of secondary emissions from the loop-top sources.

Analytic time-dependent solutions to the focused diffusion equation have been considered in the case of constant coronal B to find the basic decay time of the trapped proton number, τ_{decay}, an asymptotic value of the exponential decay time when time tends to infinity. In general case, time τ_{decay} does not coincide with the first characteristic time τ_{trap}. In the case of variable B in the coronal portion of the loop, Monte Carlo simulations of pitch-angle scattering have been employed to calculate τ_{decay} in a wide range of parameters. However, we have also obtained analytic expressions for how the characteristic time scales with parameters of the magnetic loop. Deduced expressions for τ_{decay} should be used for calculations of ion acceleration in the escape-time approximation and for the interpretation of the decay phase of solar γ-ray flares. Magnetic focusing force in the coronal portion of the loop makes acceleration more efficient than would be expected in the no-coronal-focusing approximation.

3 Divergence of open magnetic field lines:

Let us consider ion acceleration region which is permeated by a diverging static ambient magnetic field $B(\zeta)$, where ζ is a spatial coordinate along the magnetic field line extending from the solar photosphere to the interplanetary medium (Figure 1). The length of the acceleration region along B is L. Small-amplitude Alfvén turbulence is generated by an unspecified mechanism inside the acceleration region. Particle scattering at Alfvén waves results in particle diffusion and acceleration described by a Fokker-Planck equation. In the case of isotropic wave turbulence and nearly isotropic particle distribution the equation takes the form:

$$\frac{\partial n}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p} p^2 D_P \frac{\partial n}{\partial p} + \frac{\partial}{\partial \zeta}\left(D_\zeta \frac{\partial n}{\partial \zeta} - \frac{D_\zeta}{L_B} n \right) + Q(\zeta, p, t), \tag{1}$$

where $n(\zeta, p, t)$ is the number of particles per unit of the magnetic line length and per unit volume in momentum space, L_B is the focusing length. The term with the focusing length employs a magnetic field geometry and comes from the consideration of particle transport along arbitrary guiding field configuration (Earl 1981). To the best of our knowledge, this portion of the transport operator has been never incorporated into a model of stochastic acceleration of solar particles. The boundary condition at the acceleration region floor, $\zeta=0$, accounts for an effect of magnetic mirroring:

$$D_\zeta \frac{\partial n}{\partial \zeta} - \frac{D_\zeta}{L_B} n = Kn, \tag{2}$$

where Kn is a flux of precipitating particles, $K=V/(4\rho_b)$, V is particle velocity, ρ_b is magnetic mirror ratio beneath the acceleration region (Figure 1). We consider non-relativistic particles and define p as an ion momentum per nucleon. In the case of weak Alfvén turbulence, the diffusion coefficient in the momentum space, D_P, and the diffusion coefficient along the guiding magnetic field, D_ζ, can be written as

$$D_P = D_{oP}(Z/A)^{2-S} p^{S-1} \Delta_P(\zeta) \quad \text{and} \quad D_\zeta = D_{o\zeta}(Z/A)^{S-2} p^{3-S} \Delta_\zeta(\zeta),$$

where $S<2$ is a spectral index of the turbulence, functions $\Delta_P(\zeta)$ and $\Delta_\zeta(\zeta)$ account for the spatial dependencies of acceleration and diffusion, respectively. We adopt the Kraichnan phenomenology: $S=3/2$. We also suggest that the Alfvén speed, the relative energy density of turbulence, and a minimum wave number in the power law spectrum of turbulence are constant throughout the acceleration region, and the injection into the acceleration is proportional to the ambient plasma number density. We suggest that all particles are instantly injected with some small momentum and consider time-integrated proton distribution functions. Magnetic field is exponential: $B(\zeta)=B_o\exp(-\eta\zeta / L)$, where η being a magnetic scale parameter.

Monte Carlo method has been employed for numerical solving equation (1). We consider exponential magnetic field and exponential injection being proportional to the ambient plasma number density. More details about numerical simulations and about analytical work can be found in the journal publication (Kocharov et al., 1999b). We finally calculate energy spectra of interplanetary and interacting protons, and the ratio of numbers of interplanetary to interacting protons, Γ. For a convenience of the result presentation, we introduce a characteristic energy of accelerated protons:

$$E_1 = (U_A \, L_\eta / \Lambda_o)^{4/3} \quad \text{MeV},$$

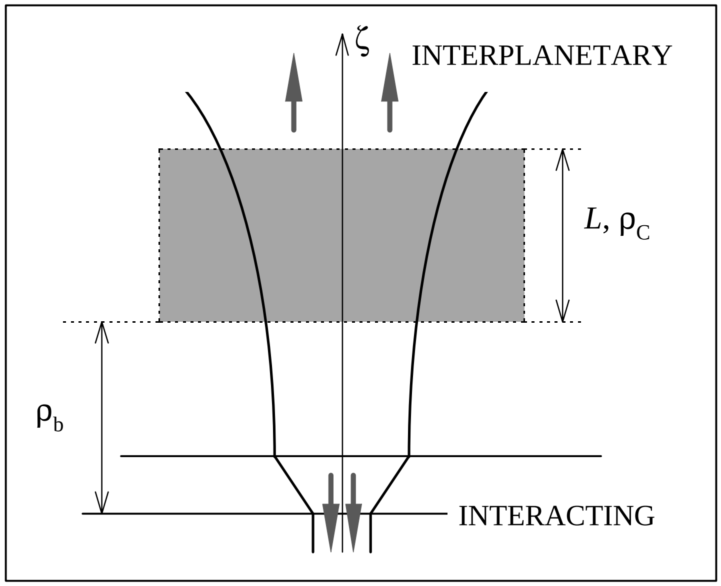

Figure 1: Illustration of the acceleration region (filled gray) where interacting and interplanetary protons may be concurrently produced; $\rho_C = \exp \eta$.

where Λ_o is the mean free path of 1 MeV proton at the floor of acceleration region, U_A is the Alfvén speed measured in units of 1.2×10^9 cm s^{-1}, L_η is an effective length of the acceleration region: $L_\eta = L\,[1-\exp(-\eta/2)] / [\eta/2]$.

Figure 2 gives calculated ratio of the numbers of interplanetary to interacting protons with energy $E>4E_1$. Parameter for the curves is an acceleration-region magnetic-scale parameter η. In Figure 2, the interplanetary to interacting proton ratio Γ is shown as a function of the mirror ratio ρ_b at a fixed value of the Λ_U/L-ratio, where $\Lambda_U \equiv \Lambda(0,p_U)$ is the mean free path of proton with energy $E_U = E_1 / [5(L_\eta /L)^2]^{2/3}$ at the acceleration region floor. Note that in the case of $\rho_b>1$, the ratio Γ depends only on a combined parameter $L/(\Lambda_U\rho_b)$. For this reason, a value of Γ corresponding to a new ratio L/Λ_U can be picked up from the same figure but at an another magnetic mirror ratio ρ_b. It is seen from Figure 2 that convergence of magnetic field lines beneath the acceleration region has no effect on the interplanetary-to-interacting proton ratio if $\rho_b<10\times L/(100\Lambda_U)$. For a proton acceleration up to above ~20 MeV under a typical coronal conditions, we estimate $L/\Lambda_U>100$, so that $\rho_b<10$ has no effect on the proton precipitation into the chromosphere, while a higher ‘magnetic elevation’ of accelerated region suggests a strong decrease in the number of interacting protons in respect to the proton number in the interplanetary medium.

4 Discussion:

We have presented the first theoretical calculations of the ratio of the numbers of interplanetary to interacting protons, Γ . An acceleration on open magnetic field lines has been considered with a view to explain relatively high values of the interplanetary-to-interacting proton ratio, Γ ~1, observed when post-impulsive-phase acceleration is present (Ramaty et al., 1993, Kocharov et al., 1996). We conclude that, in the case of stochastic acceleration, a divergence of magnetic field lines inside and beneath the acceleration region is the basic parameter affecting the ratio Γ . Deduced values of Γ in the exponential model of stochastic acceleration at $\rho_b<10\times L/(100\Lambda_U)$ vary between 1 and $\Gamma_{max}\approx5$, depending on the ‘magnetic depth’ of the acceleration region, $\rho_C= \exp \eta$ (Figures 1, 2). It would be equally incorrect to suggest that Γ is always equal to unity if particles are accelerated on open coronal magnetic field lines, or to neglect magnetic focusing inside the acceleration region arguing that $\Lambda << L_B$, or to suggest that a magnetic mirror $\rho_b\approx10$ beneath the acceleration region can cause a strong increase in Γ.

However, $\rho_b \approx 100$ could raise Γ well beyond the limiting value Γ_{max}. Spectra of low energy interacting protons, being accelerated in the exponential atmosphere, are essentially steeper than would be expected based on the escape time approximation and steeper than corresponding proton spectra in the interplanetary medium. In contrast, divergence of closed magnetic field lines results in a harder spectrum of interacting protons than would be expected when the divergence has been neglected.

For a comparison of interacting and interplanetary particles, one should deduce from experimental data a number of particles interacting at the Sun and a number of particles concurrently injected into the interplanetary medium. Such an analysis has been done for the 1990 May 24 solar flare (Kocharov et al., 1996). The number ratio for those concurrently produced interplanetary and interacting protons is estimated to be ~ 1–2. One can seen from Figure 2 that the value Γ=2 corresponds to the magnetic ratio between the top of interaction region and the top of acceleration region $\rho_{top} = \rho_b \rho_C = \rho_b \exp \eta = 20–30$. The latter corresponds to rather high altitudes in solar corona, up to ~2 solar radii, if during some tens of minutes after the end of impulsive phase protons precipitate mainly away from the strong magnetic field sites.

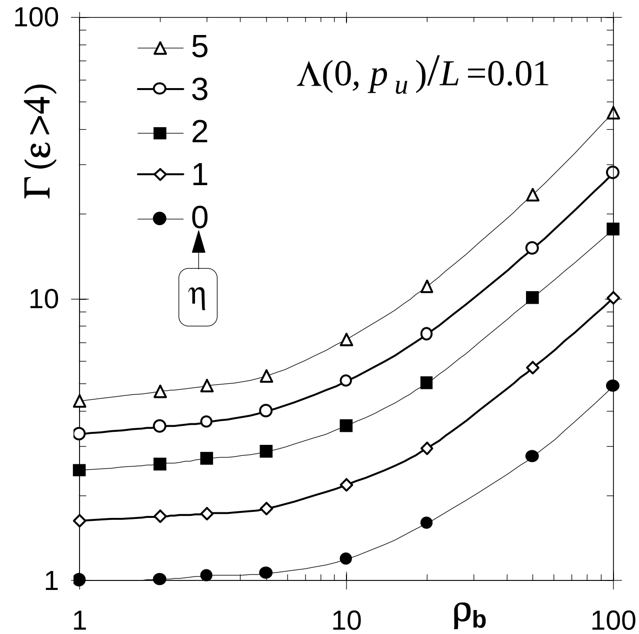

Figure 2: The ratio of the integral energy spectra of interplanetary to interacting protons, $\Gamma(E/E_1>4)$, *vs*. magnetic mirror ratio between the floor of acceleration region and the top of interacting region (ρ_b in Figure 1).

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References

Chupp, E.L., Trottet, G., Marschhaser, H., et al., 1993, Astron. Astrophys. 275, 602
Earl, J.A., 1981, ApJ 251, 739
Kocharov, L.G., Torsti, J., Vainio, R., et al., 1996, Solar Phys. 169, 181
Kocharov, L.G., Torsti, J., Tang, F., et al., 1997, Solar Phys. 172, 271
Kocharov, L., Kovaltsov, G.A., & Torsti, J., 1999a, ApJ 519, #1, in press
Kocharov, L., Kovaltsov, G.A., Laitinen, T., et al., 1999b, ApJ 521, #2, in press
Mandzhavidze, N., & Ramaty, R., 1993, Nuclear Phys. B33, 141
Ramaty, R., Mandzhavidze, N. et al., 1993, Adv. Space Res. 13, (9)275
Trottet, G., Vilmer, N., Barat, C., et al., 1993, Adv. Space Res. 13, (9)285