Two-Stage Coronal Transport of Solar Flare Particles from Magnetic Multipolarity Sources in a Flare Region

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Abstract

The transport of solar flare particles in the corona is studied. Considering the problems in terms of the characteristics of a sunspot group producing solar cosmic rays and solar flare processes, we find that formation of the fast propagation process is associated with annihilation of sunspots in the group with magnetic multipolarity. The slower propagation process depends on magnetic irregularities in the corona, and the evolution of the transport is related to the flare processes. Equations for the coronal transport are proposed and their initial and boundary conditions are given. The predicted results agree with the main observational features.

1. Introduction

There appears to be an established consensus that the azimuthal distribution of solar particles relative to the flare-observant connecting field line takes place mainly in the corona, not during interplanetary propagation.[1,2] It is shown from various observations that the azimuthal transport of flare particles in the corona occurs at two different rates: a fast propagation process which covers a longitudinal extension of about $60°-100°$ around the flare site, the so-called fast propagation region (FPR),[3–5] and a slower propagation process which is outside of the FPR and not disturbed by flare, the so-called lower propagation region (LPR).[6] According to the intensity-time profiles of wave ranges during a large solar flare, a flare process can usually be divided into three phases: the durations of the phases have typical values of 10 min, 5 min and one hour, respectively.[7] The re-flare phase is due to radiation by coronal plasma, not due to flare particles. Solar flare particles are created during the impulsive phase which is the early part of the flash phase. During the flash phase, the flare particles in the FPR are strongly diffused by the drift and scatter due to shock waves, turbulences and radios in the flare region. It is generally believed that the LPR is not disturbed by flare, and therefore that the diffusion transport of flare particles in the LPR is caused by magnetic irregularities of all scale sizes superimposed on a background of ordered magnetic fields. During the main phase, following the flash phase, turbulences in flare region become weaker and weaker. The flash phase and the main phase can, therefore, serve as rough fiducial marks for the time processes of the transport of flare particles in the corona.[8]

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2. Two-stage Transport and the Results

It has been observed that in a significant number of events the main intensity of the particle flux , and therefore, the FPR, coincides with the flare position.[9], Thus, under the one-dimension approximation,[6] we let the center of the FPR be at x=0, which is the same as that of the flare region. The particle azimuthal transport can then be described by the following equation:

$$\frac{\partial I_1}{\partial t} - D_1 \frac{\partial^2 I_1}{\partial x^2} = 0, \tag{1}$$

where I_1 and D_1 represent the particle intensity and the diffusion coefficient, respectively, in the first stage which is of about the same duration as the flash phase.

The initial condition can be written as

$$I_1|_{t=0} = N_0 \delta(x - x'), \tag{2}$$

where N_0 is the number of particles from one sunspot annihilation.

Let the extension of the FPR be $-X_0 \leq x \leq X_0$. As the number of particles inside and outside the boundaries $\pm X_0$ are the same, the boundary conditions are written in the form

$$I_1^f|_{x=\pm X_0} = I_1^s|_{x=\pm X_0}, \tag{3}$$

where I_1^f and I_1^s denote the particle intensities produced by the annihilation of one sunspot in the first stage in the FPR and LPR, respectively.

Considering equal particle beams at the boundaries, $-X_0$ and $+X_0$, between the FPR and the LPR, we have

$$D_1^f \frac{\partial I_1^f}{\partial x}\bigg|_{x=\pm X_0} = D_1^s \frac{\partial I_1^s}{\partial x}\bigg|_{x=\pm X_0}, \tag{4}$$

Here D_1^f and D_1^s are diffusion coefficients in the FPR and LPR, respectively.

As particles vanish at infinity, the condition becomes

$$I_1^s|_{x\to\pm\infty} = 0, \tag{5}$$

The solution for Eq.(1) under conditions (2), (3), (4) and (5) can be obtained by means of the Laplace transformation and the Laplace inverse transformation. It is seen from observations that a solar cosmic-ray flare occurs most often in a complex sunspot group with magnetic multipolarity.[10] Therefore, the coronal intensities of flare particles generated by annihilations of m sunspots in the sunspot group can, in the first stage , be obtained from the solution of Eq.(1) in the FPR and LPR.

In the second stage which is about the same period as the main phase, flare particles undergo both azimuthal transport and escape to interplanetary space. The equation for particle distributions is then written as

$$\frac{\partial I_2}{\partial t} - D_2 \frac{\partial^2 I_2}{\partial x^2} + \frac{I_2}{\tau} = 0, \tag{6}$$

where I_2 and D_2 represent the particle intensity and the diffusion coefficient respectively, in the second stage, and τ is the escape time. Since the second-stage initial conditions for Eq. (6) in the FPR and LPR must be the particle intensity distributions at the end of the first stage, we have

$$I_2^f(|x| \le X_0)|_{t=t_0} = F_1^f(|x| \le X_0, t_0), \tag{7}$$
$$I_2^s(x > X_0)|_{t=t_0} = F_1^s(x > X_0, t_0), \tag{8}$$
$$I_2^s(x < -X_0)|_{t=t_0} = F_1^s(x < -X_0, t_0), \tag{9}$$

where F_1^f and F_1^s denote the particle intensities produced by annihilations of m sunspots in the first stage in the FPR and LPR, respectively, t_0 is the duration from the beginning of the flare to the end of the first stage, and I_2^f and I_2^s are the particle intensities in the second stage in the FPR and LPR, respectively. The boundary conditions for Eq.(6) can be written similarly to Eqs.(3), (4) and (5).

The escape time is, as an approximation, taken to be $\tau_1 = \tau_2 = \tau$, because the flare region becomes gradually quieter during the second stage. By using the transformations: $I_2^f = I^f \exp(-t/\tau)$ and $I_2^s = I^s \exp(-t/\tau)$, the equations for I^f and I^s can be obtained from (6) as follows:

$$\frac{\partial I^f}{\partial t} - D_2^f \frac{\partial^2 I^f}{\partial x^2} = 0, \tag{10}$$
$$\frac{\partial I^s}{\partial t} - D_2^s \frac{\partial^2 I^s}{\partial x^2} = 0, \tag{11}$$

By means of the Laplace and Laplace inverse transformations, the solutions I^f and I^s of Eqs.(10), (11) can be obtained under the given conditions. Finally, using $I_2^f = I^f \exp(-t/\tau)$ and $I_2^s = I^s \exp(-t/\tau)$, the intensity-time profiles of flare particles in the second stage in the FPR have the forms

$$\begin{aligned} I_1^f \; = \; & \Bigg\{ \frac{1}{2\sqrt{\pi D_2^f t}} \int dx' \phi(x') \sum_{n=0}^{\infty} \delta_n \nu^n \Big\{ \exp\Big[-\frac{(2nX_0+x-(x')_n)^2}{4D_2^f t}\Big] + \exp\Big[-\frac{(2nX_0-x+(x')_n)^2}{4D_2^f t}\Big]\Big\} \\ & + \frac{(1+\nu)}{2\sqrt{\pi D_2^f t}} \int dx' \varphi(x') \sum_{n=0}^{\infty} \nu^n \exp\Big[-\frac{((2n+1)X_0 - \sqrt{D_2^f/D_2^s}(X_0-x') - (x)_n)^2}{4D_2^f t}\Big] \\ & + \frac{(1+\nu)}{2\sqrt{\pi D_2^f t}} \int dx' \gamma(x') \sum_{n=0}^{\infty} \nu^n \exp\Big[-\frac{((2n+1)X_0 - \sqrt{D_2^f/D_2^s}(X_0+x') + (x)_n)^2}{4D_2^f t}\Big]\Bigg\} \exp(-t/\tau), \end{aligned} \tag{12}$$

and in the LPR

$$\begin{aligned} I_2^s = & \Bigg\{ \frac{1}{2\sqrt{\pi D_2^s t}} \int dx' \varphi(x') \Big[\exp[-\frac{(x-x')^2}{4D_2^s t}] - \nu \exp[-\frac{(x+x'-2X_0)^2}{4D_2^s t}]\Big] \\ & + \frac{1-\nu}{2\sqrt{\pi D_2^s t}} \int dx' \varphi(x') \sum_{n=0}^{\infty} \nu^{2n+1} \exp\Big[-\frac{((4n+4)\sqrt{D_2^s/D_2^f}X_0 + x + x' - 2X_0)^2}{4D_2^s t}\Big] \\ & + \frac{1-\nu^2}{2\sqrt{\pi D_2^s t}} \int dx' \gamma(x') \sum_{n=0}^{\infty} \nu^{2n} \exp\Big[-\frac{((4n+2)\sqrt{D_2^s/D_2^f}X_0 + x - x' - 2X_0)^2}{4D_2^s t}\Big] \\ & + \frac{1}{2\sqrt{\pi D_2^f t}} \int dx' \phi(x') \sum_{n=0}^{\infty} \nu^n \exp\Big[-\frac{((2n+1)X_0 - \sqrt{D_2^f/D_2^s}(X_0-x) - (x')_n)^2}{4D_2^f t}\Big]\Bigg\} \exp(-t/\tau), \; (x > X_0) \end{aligned} \tag{13}$$

$$\begin{aligned} I_2^s = & \Bigg\{ \frac{1}{2\sqrt{\pi D_2^s t}} \int dx' \gamma(x') \Big[\exp[-\frac{(x-x')^2}{4D_2^s t}] - \nu \exp[-\frac{(x+x'+2X_0)^2}{4D_2^s t}]\Big] \\ & + \frac{1-\nu}{2\sqrt{\pi D_2^s t}} \int dx' \gamma(x') \sum_{n=0}^{\infty} \nu^{2n+1} \exp\Big[-\frac{((4n+4)\sqrt{D_2^s/D_2^f}X_0 - x - x' - 2X_0)^2}{4D_2^s t}\Big] \\ & + \frac{1-\nu^2}{2\sqrt{\pi D_2^s t}} \int dx' \varphi(x') \sum_{n=0}^{\infty} \nu^{2n} \exp\Big[-\frac{((4n+2)\sqrt{D_2^s/D_2^f}X_0 - x + x' - 2X_0)^2}{4D_2^s t}\Big] \\ & + \frac{1}{2\sqrt{\pi D_2^f t}} \int dx' \phi(x') \sum_{n=0}^{\infty} \nu^n \exp\Big[-\frac{((2n+1)X_0 - \sqrt{D_2^f/D_2^s}(X_0+x) + (x')_n)^2}{4D_2^f t}\Big]\Bigg\} \exp(-t/\tau), \; (x < -X_0) \end{aligned} \tag{14}$$

Here $\phi(x) = I_1^f(|x| \leq X_0, t_0), \gamma(x) = I_1^s(x < -X_0, t_0)$ and $\varphi(x) = I_1^s(x > X_0, t_0)$.

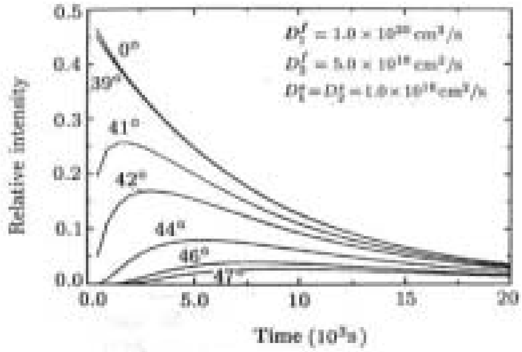

Fig. 1. Coronal time profiles of solar flare particles at seven different longitudes: within the FPR(0°,39°), and out of the FPR(41°,42°,44°,46°,47°), where the profiles take a diffusive-like form.

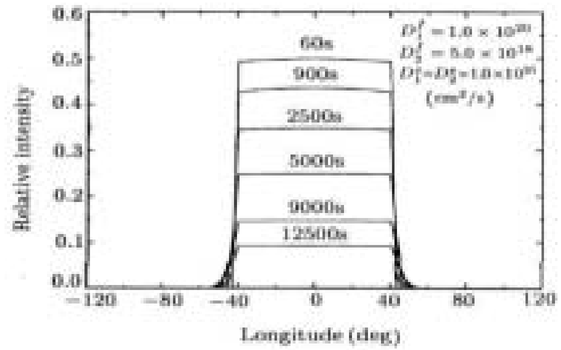

Fig. 2. Coronal azimuthal distributions of solar flare particles at different times, taking the flare site 0° as the origin of longitudinal coordinates, and opening of the FPR of width 80°.

In order to perform numerical calculations on equations(12), (13) and (14), the diffusion coefficients in the LPR during both stages are taken to be D_1^s=D_2^s=$1\times10^{16}cm^2/s$,[6] because it is not disturbed by flare. The diffusion coefficient in the FPR is taken to be $D_2^f = 5 \times 10^{18}cm^2/s$ in the second stage in order for it to match transport velocity at a rate of 60° d^{-1} (generally 24-93° d^{-1})outside of the FPR. The diffusion coefficient in the FPR in the first stage is taken to be $D_1^f = 1 \times 10^{20}cm^2/s$ because it should be much stronger than that in the second stage. Since the longitudinal extension of the FPR is about 60-100° around the flare site, it is, as an example, taken to be 80° in the calculation. Fig.1. shows the intensity-time profiles of flare particles at different coronal longitudes. Fig.2. presents the intensity-longitude profiles of flare particles. The predicted results in the figures are consistent with the following main observational properties of coronal transport, which are more or less common to most solar flare particle events.[6]

3. References

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