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Gamma-Ray Production in Stellar Winds by Galactic and Local Cosmic Rays and Application to the Heliosphere

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Abstract

The interaction of cosmic ray (CR) particles (protons, nuclei and electrons) with stellar wind matter determines the main processes of high-energy gamma ray generation through neutral pion decay and bremsstrahlung emission. These processes depend on the space-time distribution of stellar wind matter, as well as on the space-time distribution of CR energy spectrum and content. By solving self-consistent spherical-symmetric problem for stellar wind region (by taking into account energetic particle pressure influence on stellar wind plasma propagation and energetic particle kinetic stream instability influence on small-scale magnetic plasma structure), we evaluate galactic CR modulation in the star near space in dependence on the level of stellar activity, on the radial distance, on the particle energy, as well as on plasma density space-time distribution. By these results we evaluate an expected gamma-ray emission from galactic CR and gamma-ray fluxes in dependence on direction for a local observer (Heliosphere) and distant observer (stars). Then, it can be evaluated the expected gamma-ray fluxes from solar CR for great flare energetic particle events and from stars caused by local CR interactions with stellar wind matter.

1 Introduction:

Gamma ray generation in solar or stellar wind by galactic (CR) is determined mainly by 3 factors (Dorman, 1996, 1997a): (i) space-time distribution of galactic CR in the wind, their energy spectrum and chemical composition (Stecker, 1971; Dermer, 1986a, b); (ii) wind matter distribution in space and its change during activity cycle; (iii) properties of galactic CR interaction with wind matter accompanied by gamma ray generation. In some cases it could be also important: (iiii) nonlinear collective effects, i.e. the influence of galactic CR pressure and kinetic stream instability on stellar wind properties and on galactic CR propagation (Dorman, 1995); additional influence of pickup protons and anomalous component of CR on the wind extension can be also important (Roux & Fichtner, 1997).

Gamma ray generation in interplanetary space by stellar flare energetic particles is determined mainly by 3 factors (Dorman, 1996, 1997b): (i) space-time distribution of local CR, their energy spectrum and chemical composition; (ii) wind matter distribution in space and its change during stellar activity cycle; (iii) properties of local CR interaction with stellar wind matter accompanied with gamma ray generation.

2 Space-Time Distribution of Galactic Cosmic Rays in Stellar Wind:

We assume that the modulation of energy spectra of proton component of galactic cosmic rays $N_{gp}(r,E_k)$ in stellar wind can be described in a first approximation by the simple convection-diffusion model in spherical symmetrical geometry, as for the Heliosphere:

$$N_{gp}(r,E_k)=N_{gp}(E_k)\exp\left(-\frac{\gamma+2}{3}\int_r^{r_o}\frac{u(r,t)dr}{D_p(r,E_k,t)}\right)\approx N_{gp}(E_k)\exp\left(-\frac{B(t)}{R\beta}\left(1-\frac{r}{r_o}\right)\right), \quad (1)$$

where

$$N_{gp}(E_k)=2.2\left(E_k+m_pc^2\right)^{-2.75}\ proton.sr^{-1}.cm^{-2}.s^{-1}GeV^{-1} \quad (2)$$

is the differential energy spectrum of proton component of galactic CR in the interstellar space (according to Simpson, 1983), $u(r,t)$ is the stellar wind velocity, R the particle rigidity for protons (in GV), β the particle velocity in units of light speed c, and $B(t)$ the parameter of modulation. According to Dorman & Dorman (1967), Zusmanovich (1986) and Belov et al. (1990), for the Heliosphere the parameter $B(t)$ changes with solar activity in a first approximation as $B(t)\propto W^{1/3}$, where W is the sunspot number. Near the minimum of solar activity $B_{\min} \approx (0.3 \div 0.4)GV$. In solar activity maximum the modulation becomes higher and $B_{\max} \approx (1.2 \div 1.6)GV$, in dependence of direction of solar general magnetic field and sign of CR particles charge (influence of drift effects on the galactic CR modulation). Parameter $B(t)$ and dimension of CR modulation region in dependence of particle rigidity R can be evaluated more exactly by investigating hysteresis phenomena in long-term galactic CR modulation (Dorman et al., 1999).

3 Flare Energetic Particle Space-Time Distribution in the Stellar Wind:

We assume that in a first approximation the space-time distribution of stellar flare energetic particles (local cosmic rays) can be described as for the Sun (Dorman & Miroshnichenko, 1968; Dorman & Venkatesan, 1993; Stoker, 1995) by the solution of isotropic diffusion from an instantaneous and point source $Q_i(E_k,\mathbf{r}',t')=N_{oi}\delta(\mathbf{r}')\delta(t')$, of particles of type i (protons, α and heavier particles):

$$N_i(E_k,\vec{r},t)=N_{oi}(E_k)\left[2\pi^{1/2}\left(D_i(E_k)(t-t')\right)^{3/2}\right]^{-1}\exp\left(-(\mathbf{r}-\mathbf{r}')^2/\left(4D_i(E_k)(t-t')\right)\right), \quad (3)$$

where $N_{oi}(E_k)$ is the source energy spectrum, $D_i(E_k)=\Lambda_i(E_k)V_i(E_k)/3$ the diffusion coefficient, $\Lambda_i(E_k)$ the transport path for particle scattering in the stellar wind, $V_i(E_k)$ the particle velocity.

4 Space-Time Distribution of Solar Wind Matter:

Let us assume in a first approximation the model of Parker (1963) of radial expanding stellar wind (for the Heliosphere this model is in good agreement with results of direct measurements in space):

$$n(r,\theta)=n_1(\theta)u_1(\theta)r_1^2/\left(r^2u(r,\theta)\right), \quad (4)$$

where $n_1(\theta)$ and $u_1(\theta)$ are the matter density and stellar wind speed at the latitude θ and at the distance $r=r_1$ from the star (r_1=1 AU). The dependence $u(r, \theta)$ is determined by the interaction of stellar wind with galactic CR and anomalous CR component, with interstellar matter and interstellar magnetic field, by interaction with neutral atoms penetrating from interstellar space inside the stellar wind, by nonlinear processes caused by these interactions. For the Heliosphere, according to calculations of Roux and Fichtner (1997) taking into account the pressure of galactic CR, pickup protons and anomalous component of CR, the change in solar wind velocity can be described approximately as

$$u(r)\approx u_1\left(1-b(r/r_o)\right), \quad (5)$$

where the distance to the terminal shock wave $r_0 \approx 74$ AU and b ≈ 0.13÷0.45 in dependence on sub-shock compression ratio (from 3.5 to 1.5) and on injection efficiency of pickup protons (from 0 to 0.9).

5 Generation of Gamma Radiation in the Stellar Wind:

According to Stecker (1971), Dermer (1986a,b) the neutral pion generation caused by nuclear interactions of energetic protons with hydrogen atoms can be determined by

$$F_{pH}^{\pi}(E_\pi,r,\theta,t)=4\pi n(r,\theta,t)\int_{E_{k\min}(E_\pi)}^{\infty} dE_k N_p(E_k,r,t)\langle\varsigma\sigma_\pi(E_k)\rangle dN(E_k,E_\pi), \quad (6)$$

where $N_p(E_k,r,t)$ is the CR density described by (1) or (3), $E_{k\min}(E_\pi)$ is the threshold energy for pion generation and $\langle\varsigma\sigma_\pi(E_k)\rangle$ is the inclusive cross section for the reactions $p+p\rightarrow\pi^o+$............ and

$$\int_0^{\infty}\left(dN\left(E_k, E_\pi\right)/dE_\pi\right)dE_\pi = 1. \quad (7)$$

Gamma ray emission caused by nuclear interaction of solar energetic protons with solar wind matter can be determined, according to Stecker (1971), Dermer (1986a,b), as:

$$F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right) = 2\int_{E_{\pi\min}\left(E_\gamma\right)}^{\infty} dE_\pi \left(E_\pi^2 - m_\pi^2 c^4\right)^{-1/2} F_{pH}^{\pi}\left(E_\pi, r, \theta, t\right), \quad (8)$$

where $E_{\pi\min}\left(E_\gamma\right) = E\gamma + m_\pi^2 c^4 / 4E\gamma$ and $F_{pH}^{\pi}\left(E_\pi, r, \theta, t\right)$ was given in (6). According to Dermer (1986a, b) the expected gamma ray emission described by (8) can increase by about 1.45 times if we take into account the contribution of α and heavier particles in galactic cosmic rays.

6 Expected Angular Distribution and Time Variations of Gamma Ray Flux for Local Observer:

Let us assume that the stellar wind has a radius r_o and the observer is at a distance $r_{obs} \le r_o$ from the star, and at the latitude θ_{obs}. We can determine the sight line of observation by the angle θ_{sl} computed from the equatorial plane from anti-star direction to the North. In this case the expected angular distribution and time variations of gamma ray flux from interaction of energetic protons with stellar wind matter will be:

$$F_{pH}^{\gamma}\left(E_\gamma, r_{obs}, \theta_{sl}, t\right) = \int_0^{L_{\max}\left(\theta_{sl}\right)} dL\, F_{pH}^{\gamma}\left(E_\gamma, L\left(r_{obs}, \theta_{sl}\right), t\right), \quad (9)$$

where $F_{pH}^{\gamma}\left(E_\gamma, L\left(r_{obs}, \theta_{sl}\right), t\right) = F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right)$ is determined by (8), by taking into account that

$$r = r(L) = \left(r_{obs}^2 + L^2 + 2r_{obs}L\Delta\theta\right)^{1/2}, \quad \Delta\theta = \theta_{sl} - \theta_{\mathrm{obs}},$$
$$\theta = \theta(L) = \theta_{obs} + \arccos\left(\left(r_{obs}^2 + r_{obs}L\Delta\theta\right) \Big/ \left(r_{obs}\left(r_{obs}^2 + L^2 + 2r_{obs}L\Delta\theta\right)^{1/2}\right)\right), \quad (10)$$

and

$$L_{\max}\left(\theta_{sl}\right) = r_o \sin\left[\Delta\theta - \arcsin\left(\frac{r_{obs}}{r_o}\sin\Delta\theta\right)\right] \Big/ \sin\Delta\theta. \quad (11)$$

According to (9)-(11), the expected angular distribution and time variations of gamma ray fluxes will be determined by the energy spectrum of protons outside the Heliosphere, by the parameter of modulation $B(t)$, and by solar wind parameters near the Earth's orbit $n_1(\theta, t)$ and $u_1(\theta, t)$.

According to (9)-(11), the expected gamma ray fluxes from interaction of solar energetic protons with solar wind matter will be determined by the energy spectrum of proton generation on the Sun $N_{op}\left(E_k\right)$, by the diffusion coefficient $D_p\left(E_k\right)$, and parameters of solar wind near the Earth's orbit $n_1(\theta, t)$ and $u_1(\theta, t)$.

7 Expected Time Variations of Gamma Ray Flux for Distant Observer:

Let us suppose that an observer is at the distance $r_{obs} >> r_o$. In this case

$$F_{pH}^{\gamma}\left(E_\gamma, r_{obs}, t\right) = 2\pi r_{obs}^{-2}\int_{-\pi/2}^{\pi/2}\cos\theta d\theta \int_0^{r_o} r^2 dr F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right), \quad (12)$$

where $F_{pH}^{\gamma}\left(E_\gamma, r, \theta, t\right)$ is determined by (8). Similar equations can be written for gamma ray flux time variation caused by interaction of energetic α and heavier particles with stellar wind matter.

Therefore, from interactions of galactic CR with stellar wind, a modulation with periods of stellar activity will be observed.

For stellar flare the CR propagation is important only in the inner region of wind where $u(r,\theta)$ can be considered approximately as not depending on r, and the integration over r, by taking into account that

$$\frac{2}{\sqrt{2\pi}\sqrt{2D(E_k)t}}\int_0^{r_o}\exp\left(-\frac{r^2}{4D(E_k)t}\right)dr \approx \frac{2}{\sqrt{2\pi}\sqrt{2D(E_k)t}}\int_0^{\infty}\exp\left(-\frac{r^2}{4D(E_k)t}\right)dr = 1, \quad (13)$$

gives

$$F_{pH}^{\gamma}(E_\gamma, r_{obs}, t) = \left(F_{pH}^{\gamma}(E_\gamma, r_{obs})\right)_{\max}(t_{\max}/t). \quad (14)$$

where $t_{\max}(r_1, E_k) = r_1^2/6D(E_k)$. Equation (14) shows that the total flux of gamma-rays from stellar wind generated by flare energetic particle interaction with wind matter decreases with increasing time and does not depend on the details of the event. This conclusion is correct only if the diffusion coefficient does not depend on the distance to the star.

8 Conclusions:

The obtained results show that observation of gamma rays generated in stellar winds by galactic cosmic rays and by flare energetic particles can give important information on stellar winds, on the stellar activity, on flare energetic particle spectrum and propagation parameters in stellar wind.

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