Electrogasodynamic Model of Charged Particle Acceleration in Flares of the Main Sequence Dwarf Stars

Yuri Kopysov and Yuri Stozhkov

Abstract—**Dwarf stars of the main sequence generate charged particles in stellar flares. In our Galaxy the total number of such flash stars is about 10^{11}. The power and frequency of stellar flares are enough to populate all cosmic ray spectrum up to particle energy 10^{15} eV.**

Electrogasodynamic model of charged particle acceleration in flares of dwarf stars is considered. The physical mechanism includes the acceleration of particles by electric field behind plasma shock wave originating by stellar flare.

I. Introduction

SUPERNOVA explosions are considered as the main sources of galactic cosmic rays (GCR) [1]. However, our Sun and the stars in the low part of the Main Sequence also accelerate particles in flare processes. The bulk of star population in our Galaxy makes up dwarf stars. The most of them with a later spectral class than the Sun (spectral class G2) belongs to flare-stars. These stars with frequent and powerful flares are much more active in comparison with the Sun [2]. Below it is shown that these flare-stars can provide the necessary energy of GCRs. Maximum energy of particles, which can be obtained in explosion processes, is defined by acceleration mechanism of charged particles. Mechanism of particle acceleration up to ~ 10^{15} eV in the coronal electric fields of flare-stars is considered.

II. Dwarf Stars as GCR Sources

The stellar population of our Galaxy contains ~ 2×10^{11} stars. More than 90 % of them belong to dwarf stars. These stars are in the low part of the Main Sequence. The most part of them is much more active than our Sun. In other spiral galaxies many dwarf stars are observed too. For example, the galaxy NGC4565 has halo of numerous red dwarf stars (it was observed in the infrared radiation) [3]. It is probable that our Galaxy has such halo too.

The number of dwarf stars in Galactic disc is more than 10^{11}. As these stars have low luminosity, they can be observed at the distances less than (20 – 30) pc. The red dwarfs have spots like sunspots. The ratio of total area of spots on red dwarf to star surface can get tens of percents (sometimes till 90%). For comparison, this ratio for the Sun is ≤ 0.05%.

Weak global magnetic fields and strong fields of active regions define the solar and dwarf star activity. The strength of the solar global magnetic field is ≤ 1 G and in active regions it is ~ 3 kG. These values for red dwarfs are (10-20) G and several tens kG, respectively. Numerous starspots, strong magnetic fields and their complex structure create favorable situations for frequent and powerful stellar flares. Hydrogen emission (e.g., Hα line) observed during flares is the direct proof of the existence of flare activity on these objects [2].

III. Flares on Red Dwarfs and Energy of Cosmic Rays in Galaxy

Our Galaxy has the following characteristics: radius $r_{\rm Gal} \approx$ 10 kpc, thickness of optical disc $d \approx 0.3$ kpc, The Galactic disc volume $V_{\rm disc} \approx 2.8\times10^{66}$ cm^3. The GCR energy in Galactic disc plus halo is $W_{\rm CRs} \approx 0.6\times10^{68}$ eV (the density of GCR energy was taken $w_{\rm CR} \approx 0.5$ eV/cm^3). If GCR contain in Galactic disc only, their energy is $W_{\rm GCRdisc} \approx 1.4\times10^{66}$ eV.

Let us consider stellar flares. We take that the number of active red dwarfs in our Galaxy as $N_{\rm dwarf} \approx 5\times10^{10}$. The energy of one powerful stellar flare is $w_{\rm dwarf} \approx 3\times10^{36}$ erg = 1.9×10^{48} eV [2]. Let the energy of each stellar flare is $w_{\rm dwarf} \approx 2\times10^{47}$ eV (in 10 times less than maximum value) and such flares occur each (3 – 4) days. About 10% of flare energy is transferred to cosmic rays [2]. During one year the energy released to GCRs from all active red dwarfs is about 10^{60} eV. In our Galaxy cosmic rays spend ~ (10^7 – 10^8) years. Taking into account the values given above the total energy released to GCRs from stellar flares equals to $W_{\rm GCRs} \approx (10^{67} – 10^{68})$ eV.

As the values discussed are the evaluations, we think that active dwarf stars can provide the total energy of cosmic rays in our Galaxy and halo, $W_{\rm GCRs} \approx 10^{68}$ eV. If GCRs are in Galactic disc only, the energy released to GCRs from dwarf

This work was supported in part by the Neutrino Physics Program of the Russian Academy of Sciences (RAS).

Yuri Kopysov is with the Institute of Nuclear Research of RAS, 117312 Prospect of the 60th October Anniversary Prospect, 7a, Moscow, Russia (phone: +7 495 938-17-38).

Yuri Stozhkov is with the P.N. Lebedev Physical Institute of RAS, 119991, Leninsky Prospect, 53, Moscow, Russia (phone: +7 495 485-42-63; e-mail: stozhkov@fian.fiandns.mipt.ru).

stellar flares is all the more enough to provide its total energy in Galaxy.

IV. Electric Fields in Solar and Dwarf Star Coronas

As it is known from observations, our Sun accelerates particles up to energies $E \leq 10^{11}$ eV. The solar magnetic fields of active regions could keep and accelerate particles up to $E \leq 10^{15}$ eV [4]. One of the possible ways of particle acceleration is Syrovatsky's mechanism in which the reconnection of magnetic field lines in the flare regions takes place and neutral current sheet is formed [5].

Below we present another mechanism, in which the process of stellar heat energy transformation into electric energy plays the main role. Experiments with laser beams are known. When powerful laser beam strikes crystal, the hot electrons are evaporated from crystal and dense electron cloud is formed. These clouds produce strong electric fields, which, in turn, accelerate protons and nuclei up to energies of several tens of MeV and more [6, 7, 8]. In this mechanism up to 50% of laser beam energy can be transformed into electric field accelerating particles [8]. One can expect that such kind of mechanisms can work in solar and stellar flares where the electron temperature is much higher than the temperature of environmental medium. Such electric fields can arise in a quiet stellar atmosphere when electrons have got energy, for example, from acoustic waves or ascending magnetic fields.

Let us start the investigation of solar atmospheric electricity from the simple events when electric charges have spherically symmetric distribution. In this case the Poisson's equation has the form

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\phi}{dr}\right) = -4\pi q(r), \qquad (1)$$

where $q(r) = e\Sigma Z_a n_a(r)$ is the charge volume density, $n_a(r)$ is the concentration of particles with electric charge Z in the units of electron charge ($Z_e = 1$). We will look for the solution of the equation (1) as

$$\phi_o = \text{constant} \qquad \text{at } r \leq r_o \qquad (2.1)$$

$$\phi(r) = \begin{cases} eZ\times[U_1(r)/r];\ U_1(r) = C\sin[k(r-r_o)+\delta] & \text{at } r_o < r \leq r_1 \quad (2.2) \\ eZ\times[U_2(r)/r];\ U_2(r) = D\exp[-\chi(r-r_1)] & \text{at } r_1 \leq r < \infty \quad (2.3) \end{cases}$$

$$q(r) = -\frac{eZ}{4\pi r}\frac{d^2U_k}{dr^2} = \frac{eZ}{4\pi r}\begin{cases} k^2U_1(r) & \text{at } r_o < r \leq r_1 \quad (2.4) \\ -\chi^2U_2(r) & \text{at } r_1 \leq r < \infty, \quad (2.5) \end{cases}$$

where Z is positive electric charge of the solar sphere concentrated at the photosphere level with radius $r_o \approx R_\odot$ ($R_\odot$ – radius of the Sun), $r_1 \approx 2.3\, R_\odot$ is the radius of spherical surface at the boundary between K- and F- corona. Let us take the boundary conditions as

(1). Condition of logarithm derivatives U_1 and U_2 equality (at $r = r_1$):

$$\frac{1}{U_1}\frac{dU_1(r)}{dr}\bigg|_{r=r_1} = \frac{1}{U_2}\frac{dU_2(r)}{dr}\bigg|_{r=r_1}.$$

It gives the following condition of interfacing two solutions:

$$k\,ctg\,[k(r_1 - r_o) + \delta] = -\chi$$

$$\delta = n\pi - k(r_1 - r_o) - arctg\left(\frac{k}{\chi}\right), \qquad n = 0, \pm1, \pm2, \ldots$$

(2). Continuity condition for potential ϕ at $r = r_1$:

$$U_1(r_1) = U_2(r_1).$$

It gives the relation between constants C and D:

$$D = \pm Ck / \sqrt{k^2 + \chi^2}.$$

(3). Homogeneity condition for electric field at $r \geq r_o$:

$$\frac{d^2\varphi(r)}{dr^2}\bigg|_{r=r_0} = 0$$

This additional condition gives the relation between k and χ:

$$\frac{2kr_0}{2 - k^2r_0^2} + \frac{k + \chi\,tg\,[k(r_1 - r_0)]}{\chi - k\,tg\,[k(r_1 - r_0)]} = 0 \qquad (3)$$

From these equations we can get the discrete values of k_m, taking the scale of height in the external F-corona with the use of parameter χ. These discrete values of k_m correspond to different configurations of electric charge distribution in the inner part of the solar atmosphere. In this case the energy field decrease with the increase of k_m at the same values χ and Z and the conservation of electro-neutrality condition of the Sun as a star.

(4). Electro-neutrality condition

The density of volume charge q defined by formulas (2.4) and (2.5) depends on constant C, which can be found from the electro-neutrality condition. Let us write this condition as

$$eZ + \int_{r_0}^{\infty} 4\pi qr^2\,dr = 0. \qquad (4)$$

After integration one can find

$$C = (\sin\delta - kr_0\cos\delta)^{-1} \qquad (5)$$

The solutions do not depend on the value Z and can be used to describe the electric fields of solar and red dwarf coronas, and of the Earth's atmosphere too. As an example we calculated electric field configuration similar to that of electric field of the Earth. The important parameter of this configuration is the decrement of the field χ at $r \to \infty$, because χ can be used to define main sizes of the field configuration: ($r_1 - r_0$) and κ_m. For $r_0 = R_\circ$ and $r_1 = 2.3R_\circ$ we took $\chi = 0.3543$. Then the first 3 values of κ_m equal to $\kappa_o = 0.8276$, $\kappa_1 = 2.1301$, $\kappa_2 = 4.0823$. The state with $m = 0$ corresponds to monotonic decrease of the field with the distance increase. At $m = 1$ the electric field strength has minimum at $r \approx 2R_\circ$ and also decreases with the distance increase. At this point the maximum values of potential barrier and electron volume density take place.

V. Solar Atmosphere as Termoemission Converter of Heat Energy into Electric one and into Energy of Accelerated Particles

In the chromosphere at the altitude $h \approx 2000$ km above the photosphere the sharp increase of temperature takes place and in the corona at $h \approx 10^4$ km the temperature reaches 10^6 K. The heating is made by the dissipation of energy of mechanical and magnetic fluxes arising from the photosphere and by the scattering light quanta on free electrons. Electrons are heated and the high - energy electrons cannot be kept by gravitation field. So, one can expect the flow of such electrons as it takes place in the laboratory conditions. The low energy electrons are kept by gravitational field and produce large-scale electric fields.

Let us write the system of equations for electron gas flow. The continuity equation of "hot" electron flow has the form

$$4\pi e r^2 n_{eh} u_{eh} = I_{eh} , \tag{5}$$

where n_{eh}, u_{eh}, и I_{eh} – volume concentration, velocity and current of "hot" electrons, respectively. Equation of momentum has the form

$$m_e n_{eh} u_{eh} \frac{du_{eh}}{dr} = -\frac{dp_{eh}}{dr} - n_{eh} Z_e e \frac{d\phi}{dr} - \frac{GM_o m_e n_{eh}}{r^2} + \sum_k P_{eh,k} , \tag{6}$$

where p_{eh} is pressure of electron gas flow, M_o - mass of the Sun, G - gravitational constant, ϕ - electric potential (see formula (2)), $\Sigma P_{eh,k}$ – total momentum transferring to ions and "cold" electrons in the volume unit. Equation of energy conservation is written

$$n_{eh} u_{eh} \left(\frac{3}{2}\kappa \frac{dT_{eh}}{dr} - \frac{\kappa T_{eh}}{n_{eh}} \frac{dn_{eh}}{dr}\right) = = \frac{1}{r^2}\frac{d}{dr}\left(r^2 \lambda_{eh} \frac{dT_{eh}}{dr}\right) - \frac{3}{2}\nu n_{eh} \kappa (T_{eh} - T_{ec})$$

where T_{eh} and T_{ec} are the temperatures of "hot" and "cold" electrons, λ_{eh} – coefficient of thermal conductivity of fast electrons, ν - constant, characterizing the velocity of heat transfer from "hot" electrons to "cold" ones. There are two types of Parker's solutions corresponding to electron wind and electron breeze.

The large-scale electric fields considered arise from the interaction of several Maxwell's groups of electrons – running electrons of electron wind and returning electrons of electron breeze. Besides these flows, the fluxes of electrons and ions accelerated by electric field are produced. These fluxes compensate negative electric charge which solar wind carries away. Thus, the current circuit of coronal thermo-emission converter is closed and such converter is working at the background of neutral solar wind. The source of energy is the thermal energy of "hot" electrons. The existence of be-Maxwell's electron spectrum in the solar wind at $r = 1$ a. e. ($T_{eh} = 6.9 \times 10^5$ K and $T_{ec} = 1.25 \times 10^5$ K) is the confirmation of this model [9].

One can consider two stage of the acceleration process. At the first stage the hot electrons' cloud leads positive ions (process is like the ambipolar diffusion) and electric field is produced between clouds of the hot electrons and ions. Maximum energy which can get a positive ion is $E_m \le Mc^2\gamma$, where Mc^2 is the rest energy of ion and γ is the Lorentz-factor of electron cloud. If flare temperature can get ~ 10^8 K then the value of E_m will be several tens of MeV. Second stage of the positive ions acceleration is due to the large-scale electric field arising between two clouds. This field will accelerate ions up to energies $E \sim \varepsilon L$ where ε is the electric field strength and L is the linear scale of electric field. If we take $\varepsilon \approx 100$ V/cm and $L \approx 10^{13}$ cm then one has got $E_m \approx 10^{15}$ eV.

We suppose that the overturning shockwave front and/or ion-sound turbulence could be responsible for ion injection.

VI. Red Dwarfs and Problem of Cold Dark Matter

Hypothesis on red dwarfs as CGR sources involves the problem of cold dark matter (CDM) in Galaxy. The signature of CDM can be high-energy γ-quanta. Neutralino, as weakly interacting particle, is the widely discussed candidate on the role of CDM particle. The annihilation of neutralino pairs produces high-energy γ-quanta and antiprotons as by-product of this reaction. The new results were obtained by processing data of the detector EGRET [10]. The excess of galactic high-energy γ-quanta (0.1 –10 GeV) over background expected in γ-ray spectrum from GCR was found. The authors of the paper consider this result as the indicator of CDM presence in Galaxy (neutralino annihilation, if the neutralino mass is (50-100) GeV). In this case one can expect the excess flux of antiprotons in the energy range of (10-30) GeV. If this excess of antiprotons exists, it will be soon detected by experiment PAMELA [11]. In the case of negative result of PAMELA experiment, the excess of high-energy γ-quanta will testify that flare red dwarfs can be sources of these γ-quanta, and that averaged γ-spectrum has an universal form as it was observed by EGRET γ-telescope.

VII. Conclusion

- The energy released into cosmic rays during the flares on dwarf stars is enough to explain the density of cosmic ray energy observed in our Galaxy, both in Galactic disc and in halo.

- When upper chromosphere and low corona are heated the detachment of electrons from ions takes place and the large-scale electric fields are produced. These fields accelerate charged particles up to high energies. The strongest electric fields arise from solar flares when temperature reaches $10^7 – 10^8$ K.

REFERENCES

[1] G.B. Yodh, "Cosmic Rays, Particle Physics and High Energy Frontier," *Proceedings of the 29-th ICRC,* Pune, India, August 3-10, 2005, v. 10, pp. 11-36.

[2] P.E. Hershberg, "*Solar type activity of Main Sequence stars*," Odessa, Astroprint, 2002, 688 pp. (in Russian).

[3] Physics of space, "*Small Enciclopedia*", СЭ, Moscow, 1986, 632 pp. (in Russian).

[4] Yu.S Kopysov, Yu.I. Stozhkov, "About cosmic ray sources with energies up to ($10^{13} – 10^{14}$) eV," *Proceedings of the 29-th ICRC,* Pune, India, August 3-10, 2005, v. 3, pp. 141-144.

[5] I.M. Podgorny, A.I. Podgorny, "Acceleration of particles in current sheet," *Izvestiya Russian Academy of Sciences*, ser. phys., 1997, v. 61, No. 6, pp. 1067-1069 (in Russian).

[6] S.P. Hatchet, C.G. Brown, T.E. Cowan, et al., "Electron, photon, and ion beams from relativistic interaction of Petawatt laser pulses with solid target," *Phys. Plasmas*, 2000, v. 7, No. 5, pp. 2076-2082.

[7] R.A. Snavely, M.H. Key, S.P. Hatchet, et al., "Intense high-energy proton beams from Petawatt laser irradiation of solids," *Phys. Rev. Lett.,* 2000, v. 85, no. 14, pp. 2945-2948.

[8] S.G. Bochkarev, V.Y. Bychenkov, V.T. Tikhonchyk, "Investigation of ion acceleration at flying apart of laser plasma using Boltzman-Vlasov-Puasson model," *Plasma Physics*, 2006, v. 32, № 3, pp. 230-247 (in Russian).

[9] Y. Feldman, J. Asbridge, S. Beim, J. Gosling, "Solar plasma and magnetic fields", *In the book "Solar output and its variation,"* Editor O.R. White, Colorado Associated University Press, Boulder, Colorado, 1977.

[10] W.de Boer, C. Sander, V. Zhukov, A.V. Gladyshev, D.I. Kazakov, "EGRET excess of diffusive galactic gamma rays as a tracer of dark matter," *In arXiv:astro-ph/0508617 v1 29 Aug 2005.*

[11] P. Picozza on behalf of PAMELA collaboration, "Experiment PAMELA," *Proceedings of the 29-th ECRS*, Lisbon, Portugal, 2006 (in press).