A new source type of galactic cosmic rays

V.G. Sinitsyna, V.Y. Sinitsyna and Yu. I. Stozhkov

P.N.Lebedev Physical Institute, Russian Academy of Science,
Leninsky prospect 53,Moscow, 119991, Russia

E-mail: sinits@sci.lebedev.ru, stozhkovyi@lebedev.ru

Abstract. Experimental data of PAMELA and AMS-02 on proton and helium spectra at high and very high energies as well as the excess of 10 - 300 GeV positron flux cannot be explained using the diffusive models of propagation of cosmic-rays accelerated at the supernova shocks and require the existence of nearby sources of cosmic rays at the distances less than one kpc. We consider active dwarf stars as possible sources of galactic cosmic rays in the energy range up to $\sim 10^{14}$ eV. The generation of high-energy cosmic rays should be accompanied by high-energy γ-ray emission, which may be detected. Here we present the SHALON long-term observation data aimed to search for γ-ray emission above 800 GeV from the active red dwarf stars: V962 Tau, V780 Tau, V388 Cas, V1589 Cyg, GJ 1078 and GL 851.1. The TeV gamma-ray emission mostly of flaring type from these sources was detected. This result confirms that active dwarf stars are also the sources of high-energy galactic cosmic rays.

1. Introduction

Investigations of last years show that the Supernova Remnants (SNRs) could operate as powerful accelerators of cosmic-ray particles up to the energies $\sim 10^{17}$ eV [1, 2, 3]. Recent observations of several SNRs in X-rays and TeV γ-rays reveal clear signatures of accelerated particles in their shells (see [4] and references within). However, the PAMELA and AMS-02 experimental data on proton and helium spectra at high and very high energies cannot be explained using the diffusive models of propagation of cosmic-rays accelerated at the supernova shock. Also, no explanation of the excess of 10 - 300 GeV positron flux detected by PAMELA and AMS-02 experiments (Fig. 1). So, an interpretation of all these recent observations hints at a possible presence of nearby sources of cosmic rays at the distances less than 1 kpc from the solar system. We consider active dwarf stars as possible sources of galactic cosmic rays in the energy range up to $\sim 10^{14}$ eV. If the nearby cosmic-ray sources exist indeed, they could also generate high-energy γ-ray emission and may be observable with γ-ray telescopes.

2. On red dwarf stars and its very high energy emission

The dwarf stars belong to the G - M classes of the main sequence of stars. The number of such stellar objects is more than 90% of all stars in our Galaxy amounted about 2×10^{11} stars. The nearest of the dwarf stars are at the distance of several parsecs from our solar system. It is believed that these stellar objects are uniformly distributed inside of the galactic disc [5]. These stars produce powerful stellar flares, but the flare frequency of the active red dwarf stars is uncertain. The stellar flares of active dwarf stars are sometimes taking place several times per day. The total energy release estimates as $10^{34} - 10^{36}$ ergs [5, 6, 7, 8, 9]. The total energy of cosmic rays produced by the stellar flares of dwarf stars in the Galaxy is estimated as $\sim W_{CR} \approx 10^{51} - 10^{53}$ ergs [10, 11]. This could provide the amount of energy of charged cosmic rays in our Galaxy even compared with ones provide by SN explosions [12]. The consideration

Table 1. Red stars of Flare star catalogue [5] viewed by SHALON

Source	Distance, pc	Spectral type	$F(>0.8\text{ TeV})^a$	k_γ^b	k_{Flare}^c
V388 Cas	10.5	M5V	0.84 ± 0.20	-2.51 ± 0.15	-2.91 ± 0.18
V780 Tau	10.4	m/M5.5 or M7V	0.23 ± 0.03	-2.52 ± 0.15	-3.01 ± 0.21
V962 Tau	-	-	0.39 ± 0.04	-2.54 ± 0.16	-2.95 ± 0.22
V1589 Cyg	23 - 32	dM4.5e	0.13 ± 0.02	-2.91 ± 0.18	-3.15 ± 0.29
GJ 1078	20.6	M4.5V	0.38 ± 0.14	-2.46 ± 0.48	-3.11 ± 0.49
GL 851.1	21.7	dM0e or K5V	0.55 ± 0.09	-2.54 ± 0.42	-2.32 ± 0.21

[a] Integral flux at energy > 800 GeV in units of $10^{-12} cm^{-2} s^{-1}$
[b] Index in fitting of TeV average differential spectrum in form of power low $dF/dE \propto E^{k_\gamma}$
[c] Index in fitting of TeV flare differential spectrum in form of power low $dF/dE \propto E^{k_{Flare}}$

of active dwarf stars as sources of the cosmic rays with $E \leq 10^{14}$ eV are giving us the possibility to understand anomalies in the cosmic rays recorded during the last 10 - 15 years by PAMELA, AMS-02, CALET, DAMPE [13, 14, 15, 16].

In this paper we present the results of study of the flaring active dwarf stars which supposed to be a source of cosmic-rays up to $\sim 10^{14}$ eV. Generation of high-energy cosmic rays in such flares should be accompanied by the high-energy γ-ray emission. We have used our SHALON instrument to detect the γ-rays in TeV-energy range ([4, 10, 11] and references therein). Our instrument has a wide field of view (FoV $> 8°$). In accordance with the long-term program studying of γ-ray sources, more than ten-year-long observations of Tycho's SNR, Crab Nebula, 4C+41.63 and Cyg X-3, are being carried out in the SHALON experiment [4, 11] . When we observed these sources, the dwarf stars listed in the Table 1 were in our telescope field of view, also. Thus, simultaneously we had long-term observations of these stellar objects. The data obtained during more than 10 years observations of the dwarf stars V388 Cas, V962 Tau, V780 Tau, V1589 Cyg, GJ 1078 and GL 851.1 were analyzed.

The TeV γ-ray emission from the position of M-stars discussed was detected in SHALON experiment [10, 11] with statistical significance of $> 5\sigma$ determined by method of [17] with the average integral fluxes presented in Table 1. During the long-term observations these red dwarfs appeared as a sources with a highly variable flux at energies up to 10 TeV. Both, an average (△) and flaring (▲) spectral energy distributions was extracted and presented in Fig. 2. The shapes of energy spectra at $E > 800$ GeV can be fitted with a soft power law: $dF/dE \propto E^k$, the indices of flaring and average spectra are listed in Table 1. It was found that the duration of high flux periods corresponding to the flare spectra of the discussed red dwarfs ranges from 2 to 5 days [11]. The detected TeV γ-ray fluxes demonstrate that these objects produce flares with the total energy of $\sim 10^{34} - 10^{35}$ ergs. For comparison, the most powerful solar flares release is 10^{32} ergs.

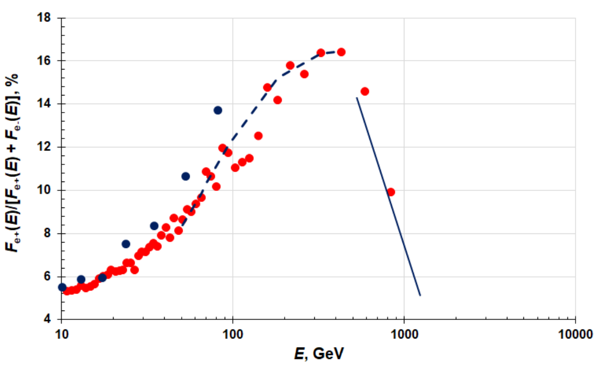

Figure 1. The ratio of e^+ flux to the sum of e^- and e^+ fluxes versus energy of these particles. Blue points are the PAMELA data and red points are the AMS-02 data. Dashed line shows the result of calculations of ratio fluxes of e^+ to $(e^+ + e^-)$ versus energy if the probability of positron release from stellar flare site is taken into account.

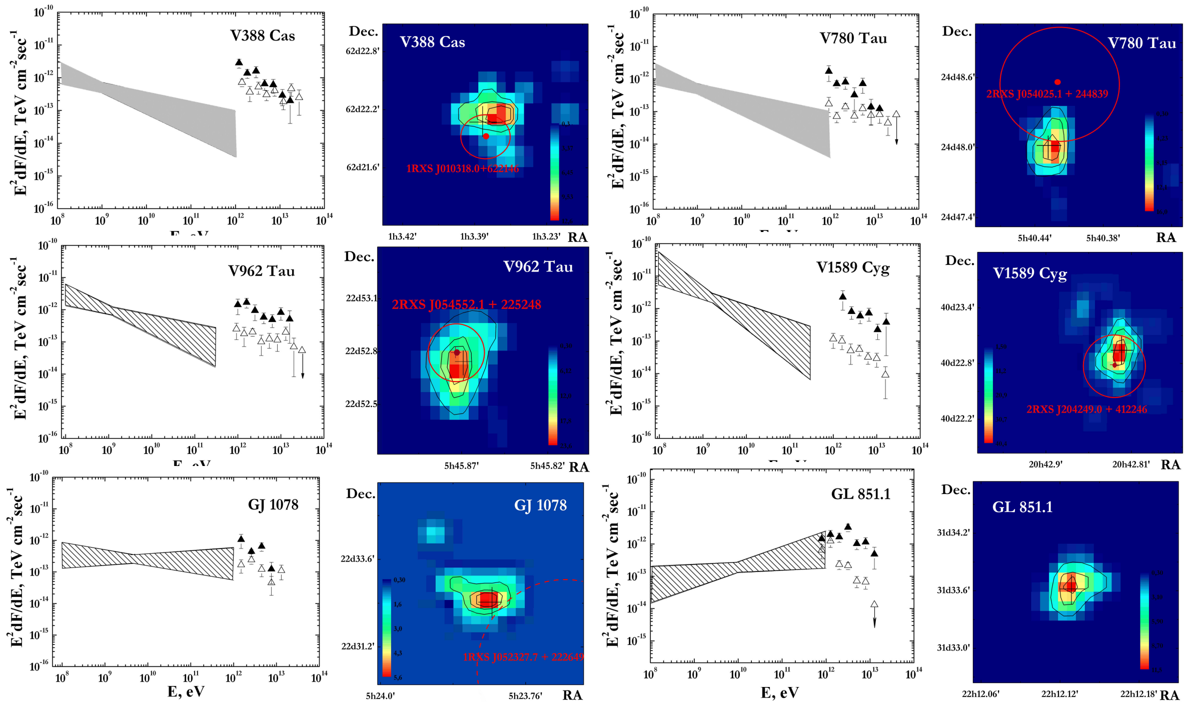

Figure 2. Spectral energy distributions of red dwarfs. △ show the average spectra and ▲ show the flaring spectra from the SHALON data. The bow tie on plots indicates the Fermi LAT data [19, 20] or minimum flux needed for a 5σ detection (see text).
Emission maps of red dwarfs by SHALON.

The searches for counterparts for the detected at very high energy M-stars in X-rays and MeV-GeV energies were performed. There is not enough information about the studies of red dwarfs in the wide energy range of the electromagnetic spectrum. But, the X-ray emission from the position of presented M-stars in the first (1RXS) and second (2RXS) ROSAT catalogue [18] was detected (see Fig. 2, right). In Fig. 2 the emission maps of listed red dwarfs by SHALON in comparison with data from X-ray data are presented. The X-ray emission (0.1 - 2.4 keV) from the position of discussed red dwarfs (error $\sim 10''$) was detected with ROSAT with energy fluxes from 3.9×10^{-13} to 2.5×10^{-12} erg cm^{-2} s^{-1} and indexes of ~ -2. It corresponds to the estimated luminosity of from 5×10^{27} erg s^{-1} to 1×10^{29} erg s^{-1}. Giving the ROSAT fluxes together with the spectral indexes it is supposed that the hard X-ray fluxes for the starting the Swift XST recording are not enough to be detectable with BAT ($\sim 10^{-9}$ erg cm^{-2} s^{-1}).

High-energy emission from unassociated sources in the vicinity of V962 Tau, V1589 Cyg, GJ 1078 and GL 851.1 at distances of $< 0.6°$ were also detected by Fermi LAT. The spectra of each of unassociated objects are presented in Fig. 2 left with bow tie and is consistent with SHALON observations of these red dwarfs at TeV energies. Unfortunately, V388 Cas and V780 Tau were not active enough after 2008 to produce a significant detection by Fermi LAT [21, 22] launched in 2008. The grey bow tie on the plots for these two objects in Fig. 2 indicates the minimum flux needed for a Fermi 5σ detection of a soft-spectrum point source. In contrast, V1589 Cyg, V962 Tau, GJ 1078 and GL 851.1 were quite active during the whole period of observations and the unassociated sources nearby detected by Fermi LAT may actually be these red dwarfs.

3. Discussion

The experimental data on the generation of TeV γ-rays by active dwarf stars given above prove that these stars are the sources of cosmic rays with energies up to $\sim 10^{14}$ eV. The energy, released in these objects is compared with one from SN explosions (for the particles with $E \leq 10^{14}$ eV).

The existence of such cosmic ray sources, nearby the solar system, allows to explain recent experimental data obtained in space during the last of 10 - 15 years.

A very important effect, discovered by the PAMELA and then confirmed by Fermi-LAT and AMS-02 is positron excess, or unexpected raise of the positron fraction, while it is expected to decrease [13]. The observed positron fraction is starting to increase at ~ 5 GeV and then goes up monotonically up to ~ 350 GeV, then at energies > 500 GeV it falls down. A possible interpretation of this effect may involve the active dwarf stars as the sources of cosmic rays up to $E \sim 10^{13}$ eV including an additional flux of positrons [23].

During the stellar flare the particles (protons, nuclei and electrons) are accelerated up to the energies of $(10^{13} - 10^{14})$ eV/nucleon. Most of these accelerated particles releases into the interstellar medium. But some of them interacts with the matter of source. These interactions give π^0 and $\pi^{\pm}$. Positrons and electrons are produced through the $\pi^{\pm}$ to $\mu^{\pm}e^{\pm}$ decay. Also, an additional source of $e^{\pm}$ is the decay of neutral pion into two γ-rays and the subsequent formation of (e^+e^-) pairs by these γ-rays. Such processes are observed during the powerful solar flares (by the way, the Sun is a yellow dwarf). These positrons and electrons have the probability to escape into the interstellar medium from a flare region where there is a strong and complex magnetic field. This probability increases with the growth of energy. If the energy of these particles $E < 5$ GeV they have no chance to escape from the flare region, but if their energy is > 300 GeV they escape from the flare region with the high probability about 100%. It gives an increase of the positron fraction observed in PAMELA, FERMI-LAT and AMS-02 experiments. As a result, this new type sources of cosmic rays provides essential addition positron flux to one produced in the interstellar medium in interactions of cosmic rays with interstellar matter. Then, at energies > 350 GeV, according to the scenario suggested in [23] (and see line in Fig. 1) the positron fraction has to decrease to the values calculated in [24] because the highest energy of accelerated particles in the stellar flares is unlikely to exceed 10^{13} eV.

References

[1] Berezhko E G & Krymskii G F 1988 *Usp. Fiz. Nauk* **154(1)** 49-91. [Sov. Phys. Usp. **31** 27-51 (1988)]
[2] Reynolds S P 2008 *Ann. Rev. Astron. Astrophys.* **46** 89-126
[3] Amato E & Blasi P 2018 *Adv. Space Res.* **62** 2731-2749
[4] Sinitsyna V G, Sinitsyna V Yu, Borisov S S et al. 2018 *Adv. Space Res.* **62(10)** 2845-2858
[5] Gershberg R E, Katsova M M, Lovkaya M N et al. 1999 *Astron. Astrophys. Suppl. Ser.* **139** 555-558
[6] Pettersen B R, Tsvetkov M K, Hawley S L et al. 1988 *Astrophysics* **19(1)** 67-73
[7] Ohm S & Hoischen C 2018, *MNRAS* **474** 1335-1341
[8] Maehara H, Shibayama T, Notsu Sh et al. 2012 *Nature* **485** L478 - L485
[9] Yang H, Liu J, Gao Q et al. 2017 *Astrophys. Journ.* **849** 36
[10] Sinitsyna V G, Sinitsyna V Y, Stozhkov Yu I 2019 *IOP: Proc. Suppl. J. Phys.: Conf. Ser.* **1181** 012018
[11] Sinitsyna V G, Sinitsyna V Yu & Stozhkov Yu I 2019 *Adv. Space Res.* **64(12)** 2585-2594
[12] Ginzburg V L, & Syrovatskii S I *The Origin of Cosmic Rays* (Pergamon Press, Oxford, 1964)
[13] Adriani O, Barbarino G C, Bazilevskaya G A et al. 2009 *Nature* **458(7238)** 607-609
[14] Adriani O, Barbarino G C, Bazilevskaya G A et al. 2011 *Science* **332** 69-72
[15] Aguilar M, Alberti G, Alpat B et al. 2013 *Phys. Rev. Lett.* **110** 141102
[16] Aguilar M, Aisa D, Alpat B et al. 2015 *Phys. Rev. Lett.* **114** 171103
[17] Li T-P, & Ma Y-Q 1983 *Astrophys. J.* **272** 317-324
[18] Boller Th, Freyberg M J, Trumper J et al. 2016 *Astron.& Astrophys.* **588** A103
[19] Acero F, Ackermann M, Ajello M et al. 2015 *Astrophys. J. Suppl. Ser.* **218(2)** 23-64
[20] *https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/*
[21] *http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm*
[22] *https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/LAT_sensitivity.html*
[23] Stozhkov Yu I 2011 *Bull. of RAS ser. Physics* **75(3)** 323-326
[24] Moskalenko I V & Strong A W 1998 *Astrophys. J.* **493** 694-707