Maximal energies of the particles accelerated by the system of converging magnetohydrodynamic flows

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Abstract. We have shown that maximal energies of the charged particles accelerated in the system of converging magnetohydrodynamic (MHD) flows can reach $\approx 10^{17}$ eV. The scheme of magnetic field amplification (MFA) applied to the previous non-linear model of particle acceleration in the colliding shocks allowed to make proper estimates for the value of turbulent magnetic field. The efficiency of the particle acceleration on the energy range larger than the "knee" in the cosmic rays spectrum ($\approx 10^{14} - 10^{15}$ eV) makes the systems of colliding MHD flows important contributors to the overall high-energy cosmic rays population in the Galaxy.

1. Introduction

Maximal energy of the charged particles attainable in supernova remnants (SNR) is one of the exciting questions of the astrophysics of cosmic rays (CR). SNR shocks are considered as the main CR accelerator up to the "knee" in the spectrum of galactic CR ($\approx 5 \cdot 10^{14}$ eV) and even further (up to $10^{16} - 10^{17}$ eV). Understanding the processes occuring on the maximal energies of the particles accelerated in the vicinity of the SNRs is extremely important [1].

Recently Ptuskin and Zirakashvili have obtained that in particular conditions the energy of protons accelerated on the shocks of different types of SNRs can reach $10^{15} - 10^{17}$ eV. Their calculations predict that for Fe-ions accelerated on IIb-type SNR the maximal energy can reach even $5 \cdot 10^{18}$ eV [1].

Recent observations and theoretical models, suggest that the maximal energy of the accelerated particle for the bulk population of SNRs is below 10^{16} eV (see, e.g., [2, 3]). The maximal energy of the proton accelerated at the SNR shock depends on shock velocity, the strength of the amplified turbulent magnetic field, the radius of SNR, and the density of the ambient medium.

The maximum energy of accelerated particles strongly differs for different types of supernovae (see e.g., [1]), it depends on the circumstellar medium around the supernova progenitor star. Moreover, core-collapsed supernovae produced by massive stars often occur in OB-star associations where the intense radiation of hot massive stars, powerful stellar winds and supernova shocks strongly modify the interstellar environment, producing large hot cavities of a few tens of parsec size, called superbubbles.

In the present paper we model a class of a few parsec size particle accelerators associated with collision of a young supernova shock with a fast stellar wind of a massive star. Some basic features of such systems were noticed in the previous papers [4, 5]. The modeled stage starts a

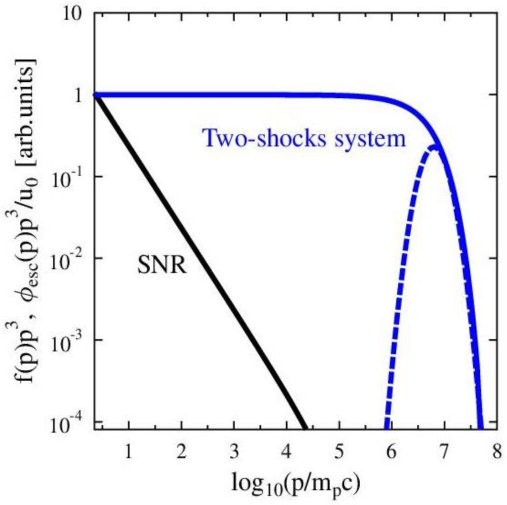

Figure 1. Spectral energy distribution of protons for the cases of acceleration on the isolated supernova shock (black line) and by the system of two colliding shocks (blue line). Dashed blue line corresponds to the spectrum of particles escaping from the system on the free escape boundary L_{FEB}.

few hundred years before the supernova shock collides with the wind termination shock. At this stage the maximal energy particles accelerated via diffusive shock acceleration mechanism (DSA) at the SNR shock reach the fast wind termination shock and are scattered back by magnetic fluctuations carried by the fast stellar wind. Therefore, the high energy particles that have mean free path $\Lambda(p)$ larger than the distance between the two shocks L_{12} start to be accelerated by the converging fast flows. This is the most favorable circumstance for the efficient Fermi acceleration. While the structure of the MHD flow in the vicinity of a supernova shell colliding with the stellar wind termination shock is rather complex, it is possible to consider a simplified plane-parallel model. When the magnetic field fluctuations are strong enough to provide the so-called Bohm diffusion regime with $\Lambda(p) = \xi r_g(p)$, where p is the particle momentum, $r_g(p)$ is the particle gyroradius in the mean magnetic field and $\xi \gtrsim 1$, the high energy particles bouncing between the converging flows are likely to have a spectrum harder than that produced at an individual shock and may contain a sizeable fraction of the total kinetic energy of the converging MHD flows.

In figure 1 we present simulated spectra for protons accelerated by the system of two colliding shocks compared with the spectrum derived for an isolated SNR. Spectra represent particle momentum distribution function $f(p)$ and particle escape flux $\phi_{esc}(p)$ multiplied by p^3. Spectral energy distribution (SED) and escape flux for the two-shocks system corresponds to the following model parameters: distance from the shock to the free escape boundary (FEB), where particles can freely escape from the system, $L_{FEB} = 3$ pc, flow velocity $u_0 = 5000$ km/s, the strength of the amplified magnetic field $B_{turb} = 275\,\mu G$ (see Section 2).

2. Maximal proton energy from colliding shocks system

Let now consider the case where SNR shock propagates into the interstellar medium (ISM) in the vicinity of the stellar wind of the nearest massive star. The efficiency of particle acceleration in the colliding shock system will increase comparing with the acceleration process on the ordinary shock. This system will characterized by hard spectral energy distribution of

Table 1. Maximal energy E_{max} of protons calculated for various model parameters, where L_{FEB} - the distance from the shock to the free escape boundary in the model [5], u_0 - the flows velocities, B_0 - the strength of the magnetic field in the vicinity of the shocks, B_{turb} - the strength of the amplified magnetic field, E_{max} - the maximal proton energy for the corresponding parameters.

L_{FEB}, pc	u_0, km/s	B_0, μG	E_{max}, eV	B_{turb}, μG	E_{max}, eV
	3000	3	$4.0 \cdot 10^{13}$		
		100	$1.3 \cdot 10^{15}$	228	$2.5 \cdot 10^{15}$
	5000	3	$6.2 \cdot 10^{13}$		
3		100	$1.9 \cdot 10^{15}$	275	$5.0 \cdot 10^{15}$
	10000	3	$2.0 \cdot 10^{14}$		
		100	$6.3 \cdot 10^{15}$	305	$1.3 \cdot 10^{16}$
	3000	3	$2.1 \cdot 10^{14}$		
		100	$6.3 \cdot 10^{15}$	239	$1.6 \cdot 10^{16}$
	5000	3	$3.2 \cdot 10^{14}$		
5		100	$1.3 \cdot 10^{16}$	281	$2.5 \cdot 10^{16}$
	10000	3	$6.4 \cdot 10^{14}$		
		100	$2.6 \cdot 10^{16}$	310	$8.0 \cdot 10^{16}$
	3000	3	$4.0 \cdot 10^{14}$		
		100	$1.3 \cdot 10^{16}$	265	$4.0 \cdot 10^{16}$
	5000	3	$5.1 \cdot 10^{14}$		
10		100	$2.1 \cdot 10^{16}$	296	$6.3 \cdot 10^{16}$
	10000	3	$1.3 \cdot 10^{15}$		
		100	$4.1 \cdot 10^{16}$	334	$1.6 \cdot 10^{17}$

accelerated particles, high efficiency of the acceleration, and increasing maximal energy of the particle for the time of efficient acceleration [5, 6].

Main features of these systems were investigated in the recent papers [4, 5, 6]. We have performed the non-linear model of particle acceleration in the two approaching magnetohydrodynamical (MHD) flows, having taken into account the flow modification by the pressure of the accelerated particles [5]. This model is based on the generalization of the semi-analytical model originally developed by Amato, Blasi and Caprioli [7, 8]. Their model was expanded for the case of two colliding shocks. We have concluded that due to the high efficiency of the particle acceleration on the colliding shocks system and extremely hard spectral energy distribution the maximal energy of the particles accelerated via such a system can be an order of magnitude (or even more) larger than it is for the isolated SNRs.

In the Table 1 we list the values of calculated maximal energy of protons accelerated by the two-shocks symmetric system. Numerical simulations were made via non-linear model of colliding shocks with free escape boundary [5]. The previous non-linear model was implemented by magnetic field amplification (MFA) procedure. It allowed us to calculate the values of turbulent magnetic field based on the calculated growth rates of plasma instabilities (see, e.g., [9, 10]). There was made the analysis for the dependence of the maximum possible proton energy E_{max} from different parameters, such as: L_{FEB} - the distance from the shock to the free escape boundary in the model [5], where particle escape from the acceleration area, u_0 - the flow velocity (we consider here symmetric model and velocities of the colliding flows accepted as equal), B_0 - the strength of the magnetic field in the vicinity of the shocks, B_{turb} - the strength of the amplified magnetic field. The density of the interstellar medium was taken as $n_0 = 1.0\ cm^{-3}$.

We consider E_{max} as the energy that corresponds to the maximum of the escape flux. For the model sets without MFA procedure the magnetic field B_0 was treated as free parameter instead of MFA setups where B_{turb} was calculated self-consistently. It is clearly seen that the maximal energy of proton grows up with the increase of the corresponding parameters. With included magnetic field amplification E_{max} confidently exceeds 10^{16} eV (see the last two columns in the Table 1).

It should be pointed out that the number of SNRs of IIb type, which accordingly to the research [1] can accelerate ions up to 10^{18} eV, is not very large and amounts only 1-2% from the full number of galactic SNRs [11]. Compare to these SNRs two-shocks systems have a higher efficiency of particle acceleration. Due to the hard spectrum of energetic particles the emissivity of these systems in a high energy range can by the order of magnitude exceed the emissivitiy of the isolated SNRs. Therefore these accelerators can be one of the important contributors to the cosmic rays population in the energy range $10^{15} - 10^{17}$ eV for the time of it's efficient acceleration (< 1000 yrs). Furthermore, these systems can be responsible for some "fluctuations" in the galactic CR spectrum in the energy range $10^{15} - 10^{17}$ eV [12, 13].

3. Discussion

It should be noted that the stage of the closely approaching SNR and stellar wind flows that is favorable for particle acceleration typically lasts for 200-1,000 years depending on the stellar wind velocity and the termination shock radius. Therefore, such sources can likely contribute to the high-energy galactic CRs population only for the time during the phase of the existence of necessary geometry (up to the moment when shocks collide and system morphology is destroyed).

The latest 2D-hydrodynamical simulations of circum-stellar medium around the rotating massive stars show that radii of their winds can reach 10 pc in size [14]. The average radii of the galactic SNRs lies around $5 - 6$ pc [11]. The efficient acceleration on two converging flows system begins only when the distance between the shocks L_{12} is less than the mean free path $\Lambda(p)$ of the energetic particle. Numerical simulations show that it occures only when $L_{12} \approx 0.1$ pc. Therefore, plane-parallel approach used in simulation is appropriate for modeling.

Maximal energies of accelerated protons attainable in the two-shocks systems allowed it to be the strong sources of high-energy gamma-emission. When the gas density of the interstellar medium in the starforming regions nearby SNR is large enough to provide efficient hadronuclear interactions of ions and protons accelerated in the system, nuclei being collided with ISM will produce π-mesons which in turn will produce gamma-photons and neutrinos. The energy E_ν of neutrino produced by p-p interactions is approximately $0.04 \cdot E_p$, where E_p - is the energy of the parent proton. It makes two-shocks systems possible sources of PeV-neutrinos detected by IceCube in 2013 [15]. For example, the system with $u_{01} = u_{02} = 5000\,km/s$, $X_{FEB} = 5$ pc, $B_{turb} = 281\,\mu G$ will produce proton with $E_p = 2.5 \cdot 10^{16}$ eV, that can be parent for the PeV neutrinos detected with IceCube. Detailed discussion of these systems as possible high-energy neutrino sources will be done in the following paper (A.M.Bykov, P.E.Gladilin, S.M.Osipov, 2014, in prep.).

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References

[1] Ptuskin V, Zirakashvili V and Seo E S 2010 *ApJ* **718** 31–36 (*Preprint* 1006.0034)
[2] Bell A R, Schure K M, Reville B and Giacinti G 2013 *MNRAS* **431** 415–429 (*Preprint* 1301.7264)
[3] Helder E A, Vink J, Bykov A M, Ohira Y, Raymond J C and Terrier R 2012 *Space Sci. Rev.* **173** 369–431 (*Preprint* 1206.1593)
[4] Bykov A M, Gladilin P E and Osipov S M 2011 *Memories of Italian Astronomical Society* **82** 800 (*Preprint* 1111.2587)
[5] Bykov A M, Gladilin P E and Osipov S M 2013 *MNRAS* **429** 2755–2762 (*Preprint* 1212.1556)
[6] Bykov A M, Ellison D C, Gladilin P E and Osipov S M 2012 *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 1505) ed Aharonian F A, Hofmann W and Rieger F M pp 46–55 (*Preprint* 1212.1985)
[7] Amato E and Blasi P 2005 *MNRAS* **364** L76–L80 (*Preprint* arXiv:astro-ph/0509673)
[8] Caprioli D, Blasi P, Amato E and Vietri M 2009 *MNRAS* **395** 895–906 (*Preprint* 0807.4261)
[9] Bykov A M, Brandenburg A, Malkov M A and Osipov S M 2013 *Space Sci. Rev.* (*Preprint* 1304.7081)
[10] Bykov A M, Osipov S M and Ellison D C 2011 *MNRAS* **410** 39–52 (*Preprint* 1010.0408)
[11] Green D A 2004 *Bulletin of the Astronomical Society of India* **32** 335–370 (*Preprint* arXiv:astro-ph/0411083)
[12] Hörandel J R 2013 *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 1516) ed Ormes J F pp 185–194 (*Preprint* 1212.0739)
[13] Berezhnev S F, Besson D, Budnev N M, Chiavassa A, Chvalaev O A, Gress O A, Dyachok A N, Epimakhov S N, Haungs A, Karpov N I, Kalmykov N N, Konstantinov E N, Korobchenko A V, Korosteleva E E, Kozhin V A, Kuzmichev L A, Lubsandorzhiev B K, Lubsandorzhiev N B, Mirgazov R R, Panasyuk M I, Pankov L V, Popova E G, Prosin V V, Ptuskin V S, Semeney Y A, Shaibonov B A, Silaev A A, Silaev A A, Skurikhin A V, Snyder J, Spiering C, Schröder F G, Stockham M, Sveshnikova L G, Wischnewski R, Yashin I V and Zagorodnikov A V 2012 *Nuclear Instruments and Methods in Physics Research A* **692** 98–105 (*Preprint* 1201.2122)
[14] Georgy C, Walder R, Folini D, Bykov A, Marcowith A and Favre J M 2013 *ArXiv e-prints* (*Preprint* 1309.1360)
[15] Aartsen M G, Abbasi R, Abdou Y, Ackermann M, Adams J, Aguilar J A, Ahlers M, Altmann D, Auffenberg J and Bai X e a 2013 *Physical Review Letters* **111** 021103