Astroparticle Physics 98 (2018) 21–27

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Cosmic ray acceleration in magnetic circumstellar bubbles

V.N. Zirakashvili*, V.S. Ptuskin

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Troitsk, Moscow 108840, Russia

ARTICLE INFO

Article history:
Received 7 December 2017
Accepted 15 January 2018
Available online 31 January 2018

Keywords:
Cosmic rays
Acceleration
Supernovae

ABSTRACT

We consider the diffusive shock acceleration in interstellar bubbles created by powerful stellar winds of supernova progenitors. Under the moderate stellar wind magnetization the bubbles are filled by the strongly magnetized low density gas. It is shown that the maximum energy of particles accelerated in this environment can exceed the ”knee” energy in the observable cosmic ray spectrum.

1. Introduction

It is well established that supernova remnants (SNRs) are efficient accelerators of protons, nuclei and electrons. They are the principle sources of Galactic cosmic rays. The diffusive shock acceleration (DSA) mechanism [1–4] can provide the acceleration of the charged particles at shocks of SNRs. During the last decades the excellent results of X-ray and gamma-ray astronomy supplied the observational evidence of the presence of multi-TeV energetic particles in these objects (see e.g. [5] for a review).

It is clear now that some magnetic amplification mechanism is needed for the acceleration of cosmic ray protons beyond PeV energies. The most popular one is the amplification in the course of the non-resonant streaming instability suggested by Bell [6]. The instability is produced by the electric current of highest energy particles escaping to the upstream region of the quasiparallel shock. In this regard the accelerated particles prepare the magnetic inhomogeneities for effective DSA themselves. It was shown recently that the similar instability operates at quasiperpendicular shocks [7].

The amplified magnetic fields indeed present in young SNRs as it was determined from the thickness of X-ray filaments [8]. The highest magnetic fields were found for young SNRs Cas A and Tycho. One can expect that the particle acceleration is very efficient in these objects. However the recent gamma ray spectral measurements performed for these remnants revealed spectral breaks or even cut-offs at TeV energy [9–12]. This means that at present the protons are accelerated to energies of the order of 10 TeV in these remnants. The maximum energies were not significantly higher in the past because of rather high shock speeds about 5000 km s^{-1} at present. The most probable explanation is the small size of magnetic disturbances generated via the non resonant streaming instability and the suppression of the effective acceleration by large scale electric fields appearing under the development of this instability [13].

On the other hand there are several more efficient cosmic ray accelerators like RXJ1713.7-3946, Vela Junior with maximum energies close to 100 TeV and without the strong magnetic amplification [5]. Probably the blast wave in these remnants propagates in the low density ($n < 0.1$ cm^{-3}) medium produced by the stellar wind of the supernova progenitor. So the unexpected results of the modern gamma-ray astronomy draw our attention to DSA in such environments.

In this paper we consider DSA in wind blown cavities. As we shall show below the magnetic field in cavities produced by powerful winds of O-stars and Wolf–Rayet (WR) stars can be high enough to provide the acceleration of cosmic ray particles up to PeV energies.

The paper is organized as follows. In the next Sections 2–4 we describe the magnetic structure and the particle acceleration in wind blown bubbles. The numeric results of magnetohydrodynamic (MHD) simulations and DSA modeling are given in Sections 5 and 6 respectively. The discussion of results and conclusions are given in Sections 7 and 8.

2. Acceleration in wind blown bubbles

Völk and Biermann suggested acceleration of cosmic rays in stellar wind cavities [14]. As the magnetic field is almost azimuthal at large distances from the progenitor star the spherical shock wave produced in the supernova explosion is quasiperpendicular. Acceleration rate at such shocks can be higher than the rate ob-

---

* Corresponding author.
E-mail address: zirak@izmiran.ru (V.N. Zirakashvili).

https://doi.org/10.1016/j.astropartphys.2018.01.005

tained in the so called Bohm limit when the scattering frequency of particles ν is comparable with the gyrofrequency Ω [15–17].

However the energy gain at the perpendicular shock is accompanied by the drift of particles along the shock surface in the direction perpendicular to the regular magnetic field. The particles get energy in the electric field $\mathbf{E} = -[\mathbf{u} \times \mathbf{B}]/c$ in the shock frame. The maximum energy is determined by the electric potential difference under the condition $\nu \ll \Omega$. For acceleration in the stellar wind the resulting maximum energy is comparable with the one obtained in the Bohm limit. It is important that the high level of MHD turbulence in the shock vicinity is not necessary for the efficient acceleration in this quasiperpendicular regime. The low level of background turbulence that presents in the stellar wind can be enough. This is contrary to the quasiparallel shocks where the high level of MHD turbulence is needed for the justification of the Bohm diffusion.

We can estimate the maximum energy $E_{\max}$ of particles using the relation $D_B(E_{\max}) = \kappa V_s R_s$, where R_s and V_s are the shock radius and speed respectively, $D_B(E) = \mathrm{v}^2/3|\Omega|$ is the Bohm diffusion coefficient of particles with velocity v, $\kappa \sim 0.03$–0.3 is the numeric factor (see the Section 6 below). This factor $\kappa = 1/3$ if the maximum energy is limited by the electric potential mentioned above.

For the steady stellar wind with the mass loss rate $\dot{M}$ and the wind speed u_w the gas density ρ and the magnetic field strength B at large distances r from the star are given by

$$\rho = \frac{\dot{M}}{4\pi u_w r^2}, \quad B = \pm \sin\theta \frac{B_s \Omega_s r_s^2}{u_w r} = \pm \sin\theta\, u_w \frac{\sqrt{4\pi\rho}}{M_w}. \tag{1}$$

Here B_s, Ω_s and r_s are the radial component of the magnetic field, the rotation rate and the radius of the star respectively and θ is the colatitude. It is more convenient to use the magnetosonic Mach number of the wind $M_w = u_w\sqrt{4\pi\rho}/B|_{\theta=\pi/2}$ below. It is related with a frequently used magnetization parameter σ that is the ratio of magnetic and kinetic energy densities of the flow as $\sigma = M_w^{-2}$. The maximum energy of particles with charge q is then

$$E^w_{\max} = 3\kappa q B V_s R_s/c = \frac{3\kappa}{M_w}\frac{qV_s}{c}\sqrt{u_w \dot{M}}$$
$$= 70\ Z\ \mathrm{PeV} \frac{3\kappa}{M_w}\frac{V_s}{c}\left(\frac{\dot{M}}{10^{-5}M_\odot \mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{u_w}{10^3\ \mathrm{km\ s}^{-1}}\right)^{1/2} \tag{2}$$

Here Z is the charge number and we use the wind parameters of WR star. Then for $M_w = 20$, $\kappa = 0.1$ and the shock speed $V_s = 10^4$ km s^{-1} that is a characteristic value for Ib/c supernovae with the ejecta mass $M_{\mathrm{ej}} = M_\odot$ and the energy of explosion $E_{\mathrm{SN}} = 10^{51}$ e.g. [18] we obtain the maximum proton energy 35 TeV.

The stellar wind is bounded by the termination shock at distance $r = R_{TS}$ where the magnetic field strength and the gas density increase by a factor of σ_{TS}, where $\sigma_{TS} \approx 4$ is the shock compression ratio. The gas flow is almost incompressible downstream of the shock and the gas velocity u drops as r^{-2}. The azimuthal magnetic field increases linearly with the distance r in this region [19–22]. This is a so called Cranfill effect [23]. At distances where the magnetic energy is comparable with the gas pressure magnetic stresses begin to influence the gas flow. We can use the energy conservation along the lines of the flow for the description of this effect

$$\frac{u^2}{2} + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} + \frac{B^2}{4\pi\rho} = \mathrm{const}. \tag{3}$$

In addition the gas density and azimuthal magnetic field strength are related as $\rho r \sin\theta / B = \mathrm{const}$. The first term in Eq. (3) can be neglected in the incompressible flow. Then the gas pressure and magnetic field strength can be found as functions of distance r in the equatorial plane $\theta = \pi/2$ (see papers [20,24–26] for details).

At large distances the magnetic energy dominates thermal and kinetic energies and drops as r^{-2} similar to the supersonic wind region but with an additional amplification factor $M_w^2/2$ of the magnetic field [21]. The same is true for the maximum energy of particles accelerated when the blast wave propagates in the downstream region of the termination shock. However the system should have the size large enough for this. We can write down these two regimes in one expression for the maximum energy of particles accelerated by the blast wave in the downstream region that is in the wind blown bubble

$$E^b_{\max} = E^w_{\max} \min\left(\frac{M_w^2}{2}, \sigma_{TS}\frac{R_s^2}{R_{TS}^2}\right) \tag{4}$$

where the maximum energy in the wind zone $E^w_{\max}$ is given by Eq. (2). So even the modest ratio $R_s/R_{TS} \sim 3$ results in acceleration to PeV energies for blast waves of Ib/c supernovae.

Note that we have a well known physical object to check our estimate given by Eq. (2). Anomalous cosmic rays that are single charged ions are accelerated up to hundreds MeV at the termination shock of the solar wind [27]. Using the solar wind parameters $V_s = u_w = 400$ km s^{-1}, $\dot{M} = 2.5 \times 10^{-14}\ M_\odot$ yr^{-1}, $M_w = 20$ and $\kappa = 1/3$ we get $E^w_{\max} = 150$ MeV.

We can use the theory of wind blown bubbles [28] to estimate the radius of the termination shock in Eq. (4). Rewriting Eq. (12) from Weaver et al. [28]

$$\frac{R_c}{R_{TS}} = \left(\frac{25}{44}\right)^{1/2}\left(\frac{15}{16}\right)^{3/4}\sqrt{\frac{u_w t}{R_c}} \tag{5}$$

and taking into account that the radius of the contact discontinuity R_c is close to the bubble radius R_b we obtain

$$\frac{R_b}{R_{TS}} = \left(\frac{25}{44}\right)^{1/2}\left(\frac{15}{16}\right)^{3/4}\left(\frac{308\pi}{125}\right)^{1/10} u_w^{0.3} t^{0.2} \dot{M}^{-0.1} \rho_0^{0.1}$$
$$\approx t_{\mathrm{kyr}}^{0.2} n_0^{0.1}\left(\frac{\dot{M}}{10^{-5}M_\odot \mathrm{yr}^{-1}}\right)^{-0.1}\left(\frac{u_w}{10^3\ \mathrm{km\ s}^{-1}}\right)^{0.3} \tag{6}$$

where ρ_0 and n_0 are the mass and number densities of the surrounding medium and we use Eq. (21) of Weaver et al. [28] for the bubble radius R_b:

$$R_b = \left(\frac{125}{308\pi}\right)^{0.2} u_w^{0.4} t^{0.6} \dot{M}^{0.2} \rho_0^{-0.2}$$
$$= 0.52\ \mathrm{pc}\ t_{\mathrm{kyr}}^{0.6} n_0^{-0.2}\left(\frac{\dot{M}}{10^{-5}M_\odot \mathrm{yr}^{-1}}\right)^{0.2}\left(\frac{u_w}{10^3\ \mathrm{km\ s}^{-1}}\right)^{0.4} \tag{7}$$

For the bubble age $t_{\mathrm{kyr}} \sim 300$ that is the expected duration of WR stage and for the density $n_0 = 10$ cm^{-3} in the parent molecular cloud the termination shock radius is a factor of 4 smaller than the bubble radius $R_b = 9$ pc. Then the last factor in Eq. (4) is of the order of 60 when the blast wave approaches the bubble boundary and the maximum energy of protons is several PeV for SNRs of Ib/c supernova. Note that the blast wave has swept up $3M_\odot$ of gas at this time and therefore is in the transition to the Sedov stage when the shock contains most of the explosion energy.

We assumed that the stellar wind is the only source of the gas in the bubble. Contrary to this assumption Weaver at al. [28] took into account the evaporation of the gas from the bubble shell. The evaporation was regulated by the thermal conductivity flux from the hot interior to the cold shell. In the real situation the conductivity can be suppressed by the azimuthal magnetic field and by the scattering of thermal electrons on magnetic perturbations in the turbulent medium of the bubble.

In the opposite case considered by Weaver et al. [28] the gas density in the bubble is significantly higher in comparison with our estimates. Then the blast wave quickly decelerated after the