Particle acceleration and nonthermal radiation in supernova remnants

Vladimir Zirakashvili
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russian Academy of Sciences, 142190 Troitsk, Moscow region, Russia
E-mail: zirak@izmiran.ru

Abstract. Cosmic ray acceleration and magnetic amplification in shell-type supernova remnants is shortly reviewed. The results on the modeling of broadband electromagnetic emission from supernova remnants are presented and compared with observations.

1. Introduction
Diffusive shock acceleration [1, 2] (DSA) in shell-type supernova remnants (SNRs) is considered as the main mechanism for production of Galactic cosmic rays. In order to explain observations, it is enough to transfer about ten percent of the mechanical energy of supernova explosion into accelerated particles. This mechanism easily produces power-law spectra with index $\gamma \approx 2$ depending on the shock compression ratio.

During the last fifteen years X-ray observations of young SNRs reveal presence of electrons with energies up to 10-100 TeV in these astrophysical objects [3, 4, 5, 6, 7, 8, 9]. The corresponding X-rays are interpreted as a synchrotron emission of these particles. The same electrons produce also some amount of gamma-radiation via inverse Compton (IC) scattering of photons of Galactic infrared radiation and microwave background radiation (MWBR). There exist a competing process - gamma-ray production by decaying pions which may be produced mainly in $pp$ interactions of accelerated protons with the gas in the remnant.

GeV and TeV gamma-rays indeed were detected from many SNRs during last years (see e.g. [10, 11, 12, 13, 14, 15, 16, 17, 18]). As examples the gamma-ray images of a young SNR RX J1713.7-3946 and an old SNR Cygnus Loop are shown in Fig.1 and 2. The hadronic interpretation of this gamma-emission will be the evidence of the production of Galactic cosmic rays which are mainly protons in SNRs.

2. Cosmic ray acceleration in SNRs
Just after the discovery of the diffusive shock acceleration it was recognized that cosmic rays can strongly change the properties of the thermal plasma in SNRs.

A diffusive streaming of particles accelerated results in a gyroresonant instability of magnetohydrodynamic (MHD) waves in the upstream region of a supernova shock [2]. Growing MHD waves in turn produce an efficient scattering of accelerated particles and make the acceleration process faster. Simple estimates of the wave growth show that magnetic perturbations may be comparable with the mean magnetic field of the thermal plasma [19].
A corresponding free path of energetic particles is comparable with their gyroradius in this case. This is a so-called Bohm diffusion.

In addition the pressure of accelerated particles may be comparable with the ram pressure of the shock $\rho u^2$, where $\rho$ is the density of the circumstellar medium and $u$ is the shock velocity. As a result the shock velocity profile is modified by the cosmic ray pressure [20, 21]. The significance of this effect depends on the number of thermal particles injected into the diffusive shock acceleration process. The theory of the injection is not complete now (see Malkov and...
However, numerical hybrid simulations [23, 24] and observations of the collisionless Earth’s bow shock [41] in the solar wind indeed show that the number of thermal ions injected at quasi-parallel shocks is high enough to produce the shock modification.

If the supernova shock is modified by the cosmic ray pressure, a significant fraction of the available mechanical energy of supernova explosion is transferred into the energy of accelerated particles. In addition, the highest energy particles escape from the remnant. The corresponding leakage of the energy results in a higher compression ratio of the strong supernova shock in comparison with the shock compression ratio $\sigma = 4$ in the ideal monatomic gas.

The results of the Monte-Carlo modeling [26], analytical results [27, 28] obtained using a plane shock approximation and the modeling of spherical modified shocks of SNRs [29, 30] show that the shock modification results in a concave spectrum of accelerated particles. The high-energy end of the spectrum is flatter in comparison with $E^{-2}$ spectrum, while low-energy particles have steeper spectra. The nonlinear models of the acceleration at a spherical shock may be used for a description of the diffusive shock acceleration in SNRs and for a calculation of the corresponding gamma-emission (see e.g. [31]).

3. Magnetic amplification in SNRs

The information about magnetic field in SNRs is very useful for understanding of the origin of gamma radiation. The matter is that the synchrotron radiation emissivity depends on the magnetic field strength. The corresponding radiation in radio- and X-ray bands is measured for all young Galactic SNRs. This means that if the magnetic field strength in the remnant is known, it is possible to estimate the amount of electrons and to check whether IC process can explain observable gamma-radiation.

The magnetic field strength in SNRs can be estimated from the thickness of the narrow X-ray filaments at the periphery of a remnant observed in almost all young SNRs. If these filaments are due to synchrotron energy losses of electrons accelerated at the forward shock, the corresponding fields are of the order of hundreds $\mu$G (see e.g. Völk et al. [32]). Interstellar magnetic field of the order of 10 $\mu$G is significantly amplified according to these estimates. If these estimates are correct, the gamma-rays observed from most of the young SNRs have a hadronic origin. However, there exist another point of view (Pohl et al. [33]). Narrow X-ray filaments are explained by decay of magnetohydrodynamic (MHD) turbulence downstream of the shock according to this interpretation. The magnetic field strength may be lower in this case.

Amplified magnetic fields will also result in faster diffusive shock acceleration. The maximum energy of protons accelerated in SNRs may reach a so-called ”knee” energy $3 \times 10^{15}$ eV that is an order of magnitude higher than the previous estimate of Laggage and Cesarsky [34].

The most popular model of the magnetic amplification was suggested by Bell [35]. The diffusive electric current of accelerated particles upstream of the shock may be so strong, that it changes dispersion relation of MHD waves significantly. An exponentially growing mode appears with plasma motions and magnetic field disturbances in the perpendicular to the electric current direction. MHD modeling of this non-resonant cosmic ray streaming instability confirmed that magnetic field may be amplified [35, 36, 37, 38].

It was also found that the instability produces strong density inhomogeneities in the upstream region. The interaction of this perturbations with the shock front results in the front deformation and strong turbulent motions downstream of the shock. The turbulent motions are mainly in the direction of the mean gas velocity. They stretch magnetic field in the same direction and maintain the high level of amplified field inside a rather wide region downstream of the shock [39].

The schematic picture of the magnetic field amplification in the vicinity of the SNR shock with accelerated particles is shown in Fig.3. The highest energy particles accelerated run-away from the shock into the upstream region. The electric current of these particles results in
the non-resonant streaming instability. Unstable magnetic spirals expand in the parallel to the shock plane direction. Collisions of neighboring spirals results in the appearance of weak shocks and corresponding density perturbations upstream of the shock. When the shock reaches these perturbations, its surface is corrugated and turbulent motions in the downstream region are generated. Magnetic field pre-amplified upstream of the shock is further amplified by the shock compression and stretched by turbulent motions downstream of the shock. This chaotic magnetic field provide an efficient scattering of energetic particles that is necessary for diffusive shock acceleration to work.

Figure 3. The schematic picture of the magnetic field amplification in the vicinity of a SNR shock with accelerated particles.

4. Radioactivity and electron acceleration in SNRs

It became clear recently that radioactivity of supernova ejecta can result in generation of suprathermal electrons and positrons which are injected into DSA at forward and reverse shocks of supernova remnants [40, 41]. This process is important because it is well known that it is not easy to inject thermal electrons into DSA. For example for the Bohm diffusion the electron energy must be higher than the energy of ions in the shock transition region that is of the order of 10-100 keV in young SNRs. For lower energies electrons will be heated only adiabatically in the transition region and will not injected into DSA.

The process considered is illustrated in Fig. 4. Suprathermal electrons and positrons are produced in the SNR ejecta via decay of $^{44}$Ti. They are picked up by the reverse shock. At

Figure 4. Schematic view of a young supernova remnant in the context of the “radioactive origin” of relativistic electrons [40]. The forward shock propagates in the circumstellar medium outward, while the reverse shock propagates into the ejecta (gray color) outward in the laboratory frame and inward in the frame of expanding ejecta. Pre-existing energetic electrons are produced in the circumstellar medium via the Compton scattering of gamma-rays from the decay of $^{56}$Co. The radioactive decays of $^{44}$Ti provide energetic electrons and positrons in the ejecta.
Figure 5. The results on the modeling of nonthermal radiation of Cas A [46]. The following basic parameters are used: \( t = 330 \) yr, \( D = 3.4 \) kpc, \( \dot{M} = 4.4 \cdot 10^{-5} M_\odot \) yr\(^{-1}\), \( E_{SN} = 1.7 \cdot 10^{51} \) erg, \( M_{ej} = 2.2 M_\odot \), the electron to nucleon ratios at the forward and reverse shocks \( K_{en}^f = 0.002 \) and \( K_{en}^b = 0.44 \). The calculations lead to the following values of the magnetic fields and the shock speeds at the present epoch: the magnetic field downstream of the forward and reverse shocks \( B_f = 1100 \) \( \mu G \) and \( B_b = 230 \) \( \mu G \) respectively, the speed of the forward shock \( V_f = 5700 \) km s\(^{-1}\), the speed of the reverse shock \( V_b = 3400 \) km s\(^{-1}\). The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), IC emission (dashed line), gamma-ray emission from pion decay (solid line on the right), thermal bremsstrahlung (dotted line on the left), nonthermal bremsstrahlung (dotted line on the right).

early times after the supernova explosion gamma-rays from decays of \(^{56}\)Co produce Compton scattered electrons in the circumstellar medium. These energetic electrons are picked up by the forward shock.

A comparable amount of suprathermal electrons may be also generated in the circumstellar medium via photoionisation of partially ionized ions accelerated at the forward shock [42].

Simple estimates show that amount of suprathermal electrons and positrons produced by these mechanisms is enough for explanation of Galactic cosmic ray electrons and positrons [43]. However a modest preacceleration of these MeV particles up to energies of the order of 100 MeV is required for this to be the case [40]. This probably happens in the turbulent upstream regions of the shocks were preacceleration by weak shocks can operate.

5. Modeling of broad-band emission in young SNRs

In this section we shall discuss the results on the modeling of broadband electromagnetic emission in SNRs.

First we consider the results for SNR Cas A. They were obtained using a new numerical model of nonlinear DSA in SNRs [43]. Spherically symmetric gas-dynamic equations are solved together with cosmic ray transport equation. The acceleration of cosmic rays at modified reverse and forward shocks of SNRs is taken into account.

From the theoretical point of view the reverse shock is not significantly different in comparison with the forward shock. Acceleration at the reverse shock is not usually considered because the regular magnetic field of ejecta becomes very small after expansion of the exploded star. However it is expected that the random magnetic field is the main component of the field in the expanded
ejecta. The random magnetic field strength of the red super giant progenitor of IIP supernovae is of the order of $10^4$ G similar to the magnetic field strength in the interior of the Sun while the regular field is of the order of 1 G. After a homogenous expansion from the initial stellar radius $10^{13}$ cm up to the young SNR radius $10^{19}$ cm the frozen-in magnetic field drops down to $10^{-8}$ G. Although this value is significantly lower than the magnetic field in the interstellar medium it is enough for acceleration of particles up to 100 GeV in young SNRs. A more realistic non-homogenous expansion will result in the stretching of the field in the radial direction. This can increase the magnetic field strength and the ion injection efficiency at the reverse shock. Magnetic fields can be also amplified by the non-resonant CR streaming instability suggested by Bell [35].

The preliminary results on the spectral modeling of SNR Cas A [46] are shown in Fig.5. The parameters of the remnant are given in the figure caption. We show the results obtained in the framework of the hadronic origin of gamma-emission in this SNR.

The electron injection was taken in accordance with radioactive scenario described in the previous Section. The energy density of electrons and positrons at the reverse shock is high and is comparable with the total energy density in the SNR shell. Since the number density of the circumstellar medium around Cas A is known from X-ray observations the effective acceleration at the forward shock of Cas A is excluded by existing gamma-ray observations [10, 13, 14, 16]. That is why it was assumed that forward shock is not modified by cosmic ray pressure. This probably related with azimuthal magnetic field of the stellar wind where the forward shock of Cas A propagates. On the other hand almost all electromagnetic radiation is produced by the reverse shock of Cas A modified by the pressure of accelerated electrons, positrons and ions.

Gamma-rays from IC scattering and nonthermal bremsstrahlung give a non-negligible input in the model. We found that a pure leptonic model is also possible for Cas A [46].

Figure 6. Gamma-ray spectrum of SNR RX J1713.7-3946 and results on the modeling of gamma-emission in the framework of hadronic models [14].

The gamma-ray spectra and results on the spectral modeling of SNR RX J1713.7-3946 are shown in Fig.6,7. Leptonic and hadronic origin of gamma-emission are possible for this object. The main problem of the hadronic model is the absence of thermal X-rays from this remnant. For parameters of hadronic model and solar abundance of the circumstellar medium X-ray emission might be observed [44]. Since thermal X-rays are not observed in this remnant we
conclude that hadronic model is possible only if the abundance of heavy elements is several times lower in comparison with the solar abundance. This is possible because the fluctuations of the chemical composition are observed in the interstellar medium.

On the other hand the leptonic model have no problems with the absence of thermal X-rays because the gas density is low. In addition the spectral shape is better reproduced in this model.

The spectrum of another bright source of gamma-rays Vela Junior SNR (RX J0852.0-4622) is shown in Fig.8. The measured spectrum is consistent with the hadronic model of Berezhko et al. [31]. However leptonic model is not excluded for this source also [18].

The best candidate to produce the gamma-emission of hadronic origin is SNR Tycho. It was shown that it is difficult to model its broad-band spectrum (see Fig.9) using a pure leptonic
scenario [47]. A rather steep observable spectrum of gamma-rays can be explained by the presence of neutral atoms in the circumstellar medium. This reduces the compression ratio of the subshock and results in steeper spectra of accelerated protons [48]. On the other hand for a leptonic scenario IC scattering of electrons accelerated can explain observable TeV gamma-rays only if magnetic field of the remnant is lower than 100 $\mu$G. However it is difficult to explain the observed thin X-ray filaments and the radio-flux of Tycho SNR using such a low value of magnetic field.

6. Old SNRs
Gamma-rays were also detected from many old supernova remnants (IC443, CTB37, W44, W51 etc.). Their ages are above ten thousand years. The highest energy cosmic rays accelerated in these SNRs have already left them. That is why these objects show steep gamma-ray spectra or spectra with cut-offs. This permit us to estimate the maximum energies of CRs accelerated at present in these remnants and investigate how higher energy particles accelerated earlier leave.
the remnant. As examples the spectra of SNRs IC443 [15] and W44 [49] are shown in Fig.10 and 11.

The maximum energy of protons currently accelerated is about 100 GeV in the remnant IC443 and lower in the remnant W44. Such low values of maximum energy are in accordance with theoretical estimates [50]. The matter is that the cosmic ray streaming instability is not very fast in old SNRs because of low shock velocities. That is why the nonlinear damping or damping by neutrals of MHD waves limit the level of MHD turbulence and the corresponding efficiency of cosmic ray scattering by magnetic disturbances. In addition the accurate measurements of the spectrum of SNR W44 in the low-energy domain at $E < 1$ GeV permit to conclude that the gamma-emission of this remnant has a hadronic origin [49].

7. Conclusion
Our conclusions are summarized below.

1. Non-resonant streaming instability produced by the electric current of run-away CR particles results in the significant magnetic amplification at fast SNR shocks.
2. Suprathermal electrons and positrons from radioactive decay and photo-ionization can be injected into diffusive shock acceleration at supernova shocks.
3. Both leptonic and hadronic origin of gamma-emission of SNRs RX J1713.7-3946, Vela Junior and Cas A are possible.
4. Tycho SNR and old SNRs are good candidates for hadronic origin of gamma-emission.

This work is prepared under financial support of the Ministry of Education and Science in the frames of the State Contracts 16.518.11.7051 from May 12, 2011 and 14.518.11.7046 from July 20, 2012. It was also supported by RFBR 07-02-00028 grant.

References
[1] Krymsky G F 1977 Soviet Physics Doklady 22 327
[2] Bell A R 1978 MNRAS 182 147
[3] Koyama K, Petre R, Gotthelf E V, Hwang U, Matsuura M, Ozaki M and Holt S S 1995 Nature 378 255
[4] Halpern J P, Camilo F, Gotthelf E V, Helfand D J, et al 2001 ApJ 552 L125
[5] Hwang U, Decourchelle A, Holt S S, and Petre R 2002 ApJ 581 1101
[6] Vink V and Laming J M 2003 ApJ 584 758
[7] Long K S, Reynolds S P, Raymond J C, Winkler P F, Dyer K K and Petre R 2003 ApJ 586 1162
[8] Bamba A, Yamazaki R, Ueno M and Koyama K 2003 ApJ 589 827
[9] Bamba A, Yamazaki R and Hiraga J S 2005 ApJ 632 249
[10] Aharonian F, et al. 2001 A&A 370 112
[11] Aharonian F, et al. 2007 A&A 464 253
[12] Aharonian F, et al. 2007 ApJ 661 236
[13] Albert J, et al 2007 ApJ 661 L92
[14] Abdo A A, et al 2010 ApJ 710 459
[15] Abdo A A, et al 2010 ApJ 712 L20
[16] Acciari V A, et al 2010 ApJ 714 163
[17] Acciari V A, et al 2011 ApJ 730 L20
[18] Katagiri H, et al 2011 ApJ 741 44
[19] McKenzie F J and Völk H J 1981 Proceedings of 15th ICRC 9 24
[20] Oxford W I, Leer E and Skadron G 1978 Proceedings of 15th ICRC 11 132
[21] Eichler D 1979 ApJ 229 413
[22] Malkov M A and Drury L O’C 2001 Reports on Progress in Physics 64 429
[23] Giacalone J, Burgess D, Schwartz S J, Ellison D C and Bennett L 1997 JGR 102 19789
[24] Gargaté L and Spitkovsky A 2012 ApJ 744 67
[25] Ellison D, Möbius E and Paschmann G 1990 ApJ 352 376
[26] Ellison D and Eichler E 1984 ApJ 286 691
[27] Berezhko E G and Ellison D C 1999 ApJ 526 385
[28] Blasi P 2004 Nuclear Physics B 136 208
[29] Berezhko E G, Elshin V K and Ksenofontov L T 1994 Astroparticle Physics 2 215
[30] Kang H and Jones T W 2006 Astroparticle Physics 25 246
[31] Berezhko E G, Pühlhofer G P and Völk H J 2009 A&A 505 641
[32] Völk H J, Berezhko E G and Ksenofontov L T 2005 A&A 433 229
[33] Pohl M, Yan H and Lazarian A 2005 ApJ 626 L101
[34] Lagage P O and Cesarsky C J 1983 A&A 125 249
[35] Bell A R 2004 MNRAS 358 181
[36] Reville B, O’Sullivan S, Duffy P and Kirk J 2008 MNRAS 386 509
[37] Zirakashvili V N, Ptuskin V S and Völk H J 2008 ApJ 678 255
[38] Riquelmi M A and Spitkovsky A 2009 ApJ 694 626
[39] Zirakashvili V N and Ptuskin V S 2008 ApJ 678 939
[40] Zirakashvili V N and Aharonian F A 2011 Physical Review D 84 083010
[41] Ellison D C, Jones C F and Ramaty R 1990 Proceedins of 21st ICRC 4 68
[42] Morlino G 2011 MNRAS 412 2333
[43] Zirakashvili V N and Ptuskin V S 2012 Astroparticle Physics in press arXiv1109.4482
[44] Ellison D C, Patnaude D J, Slane P and Raymond J 2010 ApJ 712 287
[45] Zirakashvili V N and Aharonian F A 2010 ApJ 708 965
[46] Zirakashvili V N, et al 2012 in preparation
[47] Morlino G and Caprioli D 2012 A&A 538 A81
[48] Blasi P, Morlino G Bandiera E, Amato E and Caprioli D 2012 arXiv1202.3080
[49] Giuliani A, et al 2011 ApJ 742 L30
[50] Ptuskin V S and Zirakashvili V N 2003 A&A 403 1