Detail comparison of hadronic and electronic models of gamma-ray origin in supernova remnant RX J1713.7-3946

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***Abstract*. A new numerical model of the nonlinear diffusive shock acceleration is used for modeling of particle acceleration and production of electromagnetic radiation in the supernova remnant RX J1713.7-3946. It contains coupled spherically symmetric hydrodynamic equations including forward and backward shocks and the transport equations for energetic protons and electrons. As a result we model the spectra of electromagnetic radiation and the corresponding morphology of electromagnetic emission in different energy bands and compare them with observations in order to understand the origin of the gamma-emission.**

***Keywords*: cosmic ray acceleration, supernova remnants**

I. Introduction

The diffusive shock acceleration process [24], [4], [5], [9] is considered as the principal mechanism for the production of galactic cosmic rays (CR) in supernova remnants (SNRs). A large theoretical progress in the investigation of this mechanism was achieved during last 30 years (see e.g. Malkov & Drury [26] for a review). However only during the last decade 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. Curiously we cannot firmly distinguish now between two competing processes for gamma-rays production: an inverse Compton (IC) scattering of background electromagnetic radiation by accelerated electrons (leptonic model) or a decay of neutral pions, mainly produced by accelerating protons during the interaction with the gas of the remnant (hadronic model). Though multi-TeV electrons indeed present in young supernova remnants and produce the corresponding synchrotron X-rays, the presence of the large amount of accelerated protons is also needed for the production of magnetohydrodynamic (MHD) turbulence in the vicinity of a supernova shock. Such a turbulence is the necessary condition for the efficient acceleration of energetic particles (see e.g. Malkov & Drury [26] for a review).

In this paper we shall investigate this problem in detail. For this purpose we shall use a new numerical model of nonlinear diffusive shock acceleration [37]. This model is a natural development of existing models [7], [21]. The solution of spherically symmetric hydrodynamic equations is combined with the energetic particle transport and acceleration on the forward and backward shocks of a supernova remnant. Nonlinear response of energetic particles via their pressure gradient results in the self-regulation of acceleration efficiency. The calculation of corresponding X-ray, gamma-, and radio-emission permit us to perform the direct comparison of the spectra of electromagnetic radiation and its morphology with observations.

We shall apply this model for supernova remnant RX J1713.7-3946 - the brightest TeV gamma-ray source among known shell-type supernova remnants [3]. High quality gamma-ray, X-ray spectra and images are available at present for this astrophysical object.

The details of a numerical method and the evolution of the remnant are described in the companion paper [38] from this Conference.

The paper is organized as follows. In the next Section we briefly summarize the observational information about the supernova remnant RX J1713.7-3946. The results of modeling for the cases of hadronic and leptonic scenario are presented in Sect. III and IV. Sect. V contains the discussion of our results. Our conclusions are given in the last Section.

II. Observational properties of RX J1713.7-3946

The shell-type SNR RX J1713.7-3946 was discovered by the ROSAT All-Sky Survey [29]. The following observations of ASCA, Chandra and Suzaku revealed the intence synchrotron X-ray emission [23], [34], [32], [33] without signs of thermal X-rays. The last measurements of Suzaku [32] reveal an extended X-ray spectrum with the spectral index ~ 2 and a smooth cut-off at 10 keV.

Using the association with molecular clouds the distances $D = 6$ kpc [31], $D = 1$ kpc [17] and 1.3 ± 0.4 kpc [10] were suggested.

It is expected that a circumstellar medium around progenitors of Ib/c and IIP/b supernova is strongly nonuniform. At the main sequence (MS) phase the stellar wind of progenitor creates rarefied bubble in the surrounding medium. It seems that the corresponding MS bubble is indeed found. SNR RX J1713.7-3946 is surrounded by a massive shell of molecular gas [18]. The densest cores of molecular gas (clouds C and D) are probably swept up by the forward shock of the SNR.

The remnant was detected in gamma-rays by CANGAROO [28] and HESS [2] observations. HESS observations reveal a bright almost closed shell of gamma-emission and the extended gamma-ray spectrum with the spectral index 2.1 and the spectral cut-off at 10 TeV [3].

The remnant is rather faint in radio. The recent measurements at 1.4 GHz gave the radio-intensity 23 ± 2 Jy from the whole remnant [1]. Radio and X-ray images clearly show also the inner shell of radio and X-ray emission [25], [10], [20] with an angular diameter 0.5 degrees while the angular diameter of the remnant is close to one degree.

This shell may be probably attributed to the backward shock propagating in the supernova ejecta. One should assume that electrons are accelerated also at the backward shock in order to explain the observable inner shells of X-ray and radio emission. A similar conclusion was recently obtained by Helder & Vink [19] for the backward shock of Cas A. A backward shock is generally is not considered as an efficient accelerator, because the magnetic field of ejecta might be extremely low due to a huge expansion factor of the exploded star. However if some magnetic field amplification takes place at the forward shock it may take place also at the backward shock [15]. Magnetic fields may be amplified in the course of the nonresonant streaming instability [6].

III. HADRONIC SCENARIO

The results of spectral modeling for the case of hadronic origin are shown in Fig.1. The bump at the end of IC spectrum is produced by the electrons accelerated at the backward shock. The injection efficiency of electrons is adjusted in order to reproduce the intensity of synchrotron X-rays. The relative input of the backward and forward shocks is not strictly constrained. However it is assumed that the backward shock produces at least 10% of X-ray and radio-emission. In the case considered the backward shock produces 10% of X-ray and 16% of radio-emission.

It easy to see that for this extreme case with a high acceleration efficiency the X-rays due thermal bremsstrahlung are a factor of 20 below the Suzaku X-ray data. 70% of explosion energy has already transferred to accelerated particles. The modelled radioflux is slightly below the observable value. This seems not very important since the SNR is very faint in radio and a part of the measured radioflux may be due to a background thermal radioemission.

The energy flux of thermal X-Rays has the maximum at 0.4 keV and approximately equals to the energy flux of gamma-rays from the pion decay. As was firstly noted by Katz & Waxman [22] the ratio of this fluxes does not depend on the ambient plasma density and depend only on the shock velocity and cosmic ray acceleration efficiency.

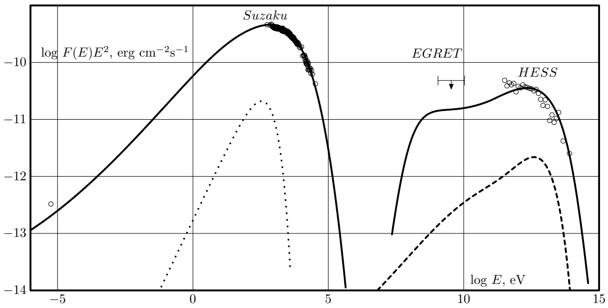

Fig. 1: The results of modeling for the hadronic scenario with parameters $t = 1050$ yr, $D = 1$ kpc, n_H =0.072 cm^{-3}, $E_{SN} = 2.0 \cdot 10^{51}$ erg, $M_{ej} = 0.67M_{\odot}$, $M_A = 23$, magnetic fields just downstream the forward and backward shocks $B_f = 146$ μG and $B_b = 24$ μG respectively, present values of the forward shock velocity $V_f = 3540$ km s^{-1} and backward shock velocity $V_f = -1980$ km s^{-1}. The following radiation processes are taken into account: synchrotron emission 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). Electron to proton ratios at the forward and backward shocks $K^f_{ep} = 7 \cdot 10^{-5}$ and $K^b_{ep} = 5.3 \cdot 10^{-4}$ were used. Experimental data of HESS [3], Suzaku [33] and radioflux 23 ± 2 Jy at 1.4GHz from the whole remnant [1] are also shown.

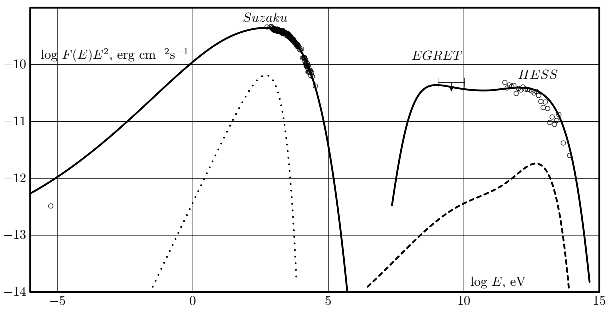

Fig. 2: The same as in Fig.1 for the hadronic scenario with Alfvénic drift in the uniform medium for parameters $t = 1020$ yr, $D = 1$ kpc, n_H =0.12 cm^{-3}, $E_{SN} = 3.0 \cdot 10^{51}$ erg, $M_{ej} = 1.2M_{\odot}$, $M_A = 23$, $B_f = 192$ μG, $B_b = 37$ μG, $V_f = 3800$ km s^{-1}, $V_f = -1920$ km s^{-1}, $K^f_{ep} = 6.5{\cdot}10^{-5}$, $K^b_{ep} = 4.0{\cdot}10^{-4}$

An agreement with HESS data will be improved if we assume the Alfvénic transport of cosmic rays downstream of the forward shock and put $\xi_A = -1$ in this region. This results in a lower effective compression ratio of the shock "seen" by accelerated particles and in the corresponding steepening of the spectra (Zirakashvili & Ptuskin [36]). Such a steepening is also desirable in theories of cosmic ray propagation in the Galaxy (see Ptuskin et al. [30]). The results are shown in Fig.2. The backward shock produces 10% of radioemission and

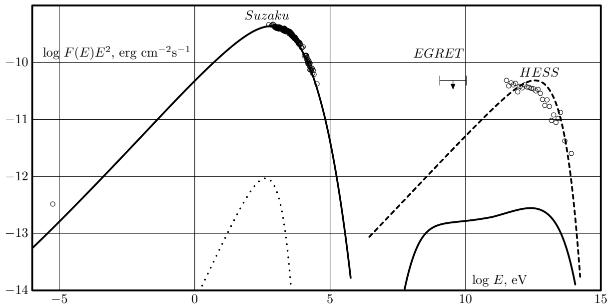

Fig. 3: The same as in Fig.1 for the leptonic scenario with unmodified forward shock for parameters $t = 930$ yr, $D = 1.5$ kpc, n_H =0.014 cm^{-3}, $E_{SN} = 2.6 \cdot 10^{51}$ erg, $M_{ej} = 0.42 M_{\odot}$, $M_A = 23$, $B_f = 15$ μG, $B_b = 21$ μG, $V_f = 6550$ km s^{-1}, $V_b = -2380$ km s^{-1}, $K_{ep}^{f} = 1.7 \cdot 10^{-2}$, $K_{ep}^{b} = 7 \cdot 10^{-4}$

25% of X-ray emission in this case. The radio emission is overproduced by a factor of 3. The agreement with radio data may be achieved if the magnetic field downstream of the forward shock drops faster than was assumed.

We should underline that similar number density close to $n_H \sim 0.1$ were also found by Morlino et al. [27] in their hadronic models of gamma-emission of SNR RX J1713.7-3946.

IV. Leptonic scenario

The observed X-ray to gamma-ray ratio close to 15 determines the value of magnetic field strength $B \sim 15$ μG when the leptonic origin of gamma-emission in RX J1713.7-3946 becomes possible.

One of possibilities to diminish the magnetic field strength is to consider an unmodified forward shock of SNR. If the injection is not effective at the forward shock, the energy density of cosmic rays will be low and the same will be true for the amplified magnetic field. E.g. such a situation is possible for a perpendicular SNR shock propagating in the medium with an azimuthal magnetic field.

In this case we use the small injection parameter $\eta_f = 10^{-5}$ at the forward shock and the standard value $\eta_b = 10^{-2}$ for the injection parameter at the backward shock. We also use a higher value $M_A = 115$ for the forward shock. We use the distance $D = 1.5$ kpc that is close to an upper limit according to Cassam-Chenaï et al. [10] and Fukui [18].

The results are shown in Fig.3. The magnetic field strengths at the backward shock and the forward shock are comparable in this case. The energy of cosmic rays is only 10% of the explosion energy. The cosmic ray pressure at the forward shock is only 1.2% of the ram pressure $\rho_0 \dot{R}_f^2$. The particles are mainly accelerated at the backward shock. The backward shock produces 40% of radioemission and 45% of X-ray emission.

The calculated profiles of gamma-brightness are shown in Fig.4. The projection effect was taken into account.

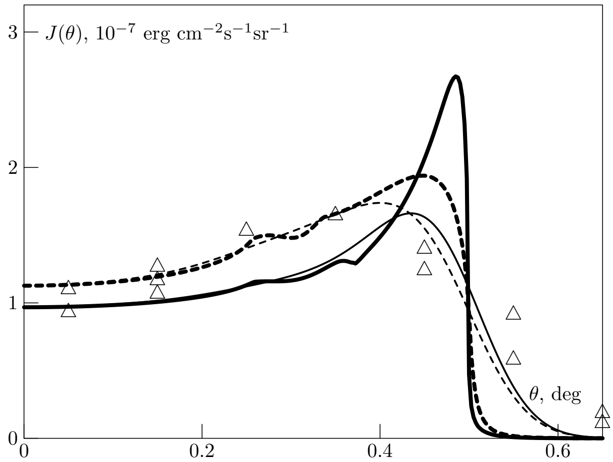

Fig. 4: Profiles of 1 TeV gamma-emission for the hadronic scenario (solid) and for the leptonic scenario (dashed). The profiles smoothed with a Gaussian point spread function of the width $\sigma = 0.05°$ are shown by the corresponding thin lines. The azimuthally averaged observable radial profile [3] is also shown (triangles).

The IC gamma-rays from the backward shock are about 5-10% in the hadronic model considered (see Sect. III). However it should be taken into account that this numbers may be higher if the backward shock produces stronger radio and X-ray emission than was assumed.

V. Discussion

Though the thermal bremsstrahlung is an order of magnitude below the Suzaku data in the hadronic models considered the actual flux of X-ray emission in this energy range will be higher due to the input of line X-ray emission [16]. The latter strongly depends on the chemical abandance of the X-ray emitting plasma. Using a solar abundance Cassam-Chenaï et al. [10] derive an upper limit $n_H < 0.02$ cm^{-3} for an ambient plasma density. This value is several times lower than $n_H \sim 0.1$ cm^{-3} in the hadronic models considered. This models are still possible if the chemical composition of the circumstellar gas is strongly different from the solar one e.g. due to absorption of X-ray line emitting ions by dust grains.

It is interesting that thermal X-rays produced in the shocked by forward shock gas are rare observed in young supernova remnants. E.g. the thermal emission of remnants Tycho and SN1006 is produced by shocked ejecta that is enriched by heavy elements [11], [12]. In this regard the SNR RX J1713.7-3946 is not a very special example. It is at a later evolutionary phase in comparison with SNRs mentioned above when the ejecta is situated deeply inside and has very low density (see Fig.2 in the companion paper [38]). This is the reason why the thermal X-ray emission of ejecta is not observed while the thermal emission from the downstream region of the forward shock is not detected similar to many other young SNRs.

VI. Conclusion

The observable ratio of forward and backward shock radii puts a rather clear constrains on the type of supernova explosion that produced SNR RX J1713.7-3946. For reasonable values of the energy of supernova explosion $E_{SN} < 3 \cdot 10^{51}$ erg the ejecta mass must be small $M_{ej} < 2M_{\odot}$. For higher masses the forward shock velocity is too low in order to produce the extended X-ray spectrum. Such small ejecta masses correspond to Ib/c or IIb core collapse supernova [14]. Circumstellar medium around these types of supernova is created by stellar winds of supernova progenitors. It may be a low density ($n_H < 0.01$ cm^{-3}) bubble created by stellar wind of progenitor during the main sequence period of the star evolution or by a stellar wind of a Wolf-Rayet progenitor. This roughly corresponds to the leptonic scenario (see Sect.IV). Or it may be a denser bubble created during a Red Supergiant stage of supernova progenitor or during the interaction of the slow Red Supergiant wind and the fast Wolf-Rayet wind. Hadronic scenario is possible in this case (see Sect.III). As we found the spectral shape of gamma-emission is better reproduced in hadronic models.

In all models considered the forward shock of SNR have swept only 6-13$M_{\odot}$. This mass is comparable or slightly smaller than the mass ejected by progenitors of Ib/c and IIb supernova during stellar evolution. This means that the shock just have swept the progenitor's material ejected during the stellar evolution. The interaction with the molecular gas surrounding the remnant only begins. The exceptions are the very dense cores of molecular gas (clouds C and D) that are situated already inside the forward shock [18]. Probably the forward shock enveloped the clouds and a high pressure gas from the downstream region drove secondary shocks into the clouds (see Chevalier [13] for a review). This shocks still interact with rarefied coronae of the clouds. It seems that the nonthermal X-rays are produced at these shocks in the cloud coronae while the highest energy gamma-rays from pion decay are mainly produced in the cloud where the target density is high [18].

Nearest results of GLAST will help to distinguish among the models considered. In the case of hadronic origin we predict the energy fluxes $F = 2 \cdot 10^{-11}$ erg cm^{-2} s^{-1} and $F = 5 \cdot 10^{-11}$ erg cm^{-2} s^{-1} at 1GeV for $\xi_A = 0$ (see Fig.1) and $\xi_A = -1$ (the model with Alfvénic drift downstream, see Fig.2) respectively. The last value is close to the upper limit of EGRET in this energy region. If GLAST will detect the gamma-rays at this level this will be a confirmation of hadronic models.

These numbers drop down to $F = 2 \cdot 10^{-12}$ erg cm^{-2} s^{-1} at 1GeV in the case of leptonic origin.

If the inner ring of SNR RX J1713.7-3946 is indeed the backward shock its proper motion may be measured. X-ray measurements may be used for this purpose since the X-ray filaments in the inner ring region were observed by Chandra [25], [34]. In all models considered the backward shock moves with several thousand kilometers per second to the center of the remnant. This value will be higher if the density increase with radius. E.g. for the "bubble" model of Berezhko & Völk [8] with r^{12} density profile the backward shock velocity is $|V_b| \sim 10^4$ km s^{-1}. So the measurement of the backward shock velocity will constrain the density distribution around this SNR.

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