Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 2 (OG part 1), pages 259–262

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Comparing a model of cosmic ray production in the supernova remnant RX J1713.7-3946 with observations

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Abstract:

Explicitly time-dependent, nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) has been employed to investigate the properties of SNR RX J1713.7-3946. Observations of the nonthermal radio and X-ray emission spectra as well as earlier H.E.S.S. measurements of the very high energy γ-ray emission were used to constrain the astronomical and the particle acceleration parameters of the system. The model assumes that the object was a core collapse supernova (SN) with a massive progenitor, has an age of ≈ 1600 yr and is at a distance of ≈ 1 kpc. It is shown that an efficient production of nuclear CRs, leading to strong shock modification and a large downstream magnetic field strength $B_{\rm d} \sim 100\ \mu$G, can reproduce the observed synchrotron emission from radio to X-ray frequencies together with the γ-ray spectral characteristics as observed by the H.E.S.S. telescopes. Small-scale filamentary structures observed in nonthermal X-rays provide empirical confirmation for this field amplification scenario which leads to a strong depression of the inverse Compton and Bremsstrahlung fluxes. The results are compared with the latest H.E.S.S. observations.

Introduction

RX J1713-3946 is an extended shell-type SNR in the Galactic plane that was discovered in X-rays with ROSAT [1]. It turns out that the observable X-ray emission is entirely nonthermal. The radio synchrotron emission is weak, with a poorly known spectral form. RX J1713-3946 was also detected in very high energy (VHE) γ-rays with the CANGAROO [2, 3] and H.E.S.S. [4, 5] telescopes. Especially the latter observations show a clear shell structure at TeV energies which correlates well with the X-ray contours from ASCA. The different observations are discussed in the paper of Berezhko & Völk ([6], hereafter referred to as BV06), on which we expand here.

The basic aim of BV06 is an investigation of the acceleration of both electrons and protons in this remnant, the calculation of the nonthermal radiation spectrum of the source using an explicitly time-dependent nonlinear kinetic theory, and a theoretical determination of the (spatial) morphology. In such a theory the particle acceleration process is coupled with the hydrodynamics of the thermal gas in the aftermath of the SN explosion.

In comparison with other SNRs (SN 1006, Cas A, and Tycho's SNR) that were successfully described within the framework of this theory and finally allowed a prediction of the γ-ray flux (see [7] for a review), the case of RX J1713-3946 is more difficult despite its spatially resolved γ-ray emission. First of all, astronomical parameters such as source distance, present expansion velocity and age are not well known. Still, following estimates from ASCA observations [8] and from NANTEN CO line measurements [9, 10] a rather close distance of $d = 1$ kpc appears indicated, and historical Chinese records suggest a low age of $t = 1614$ yr [11]. These parameters are consistent with the assumption of a core collapse SN of type II/Ib which exploded into the adiabatic, very diluted bubble created by the wind of a massive ($M < 20\ M_{\odot}$) progenitor star, whose likely compact remnant in the center is an identified neutron star (e.g. [12]). Secondly, the lack of knowledge of the spectral shape of the radio emission makes it difficult to

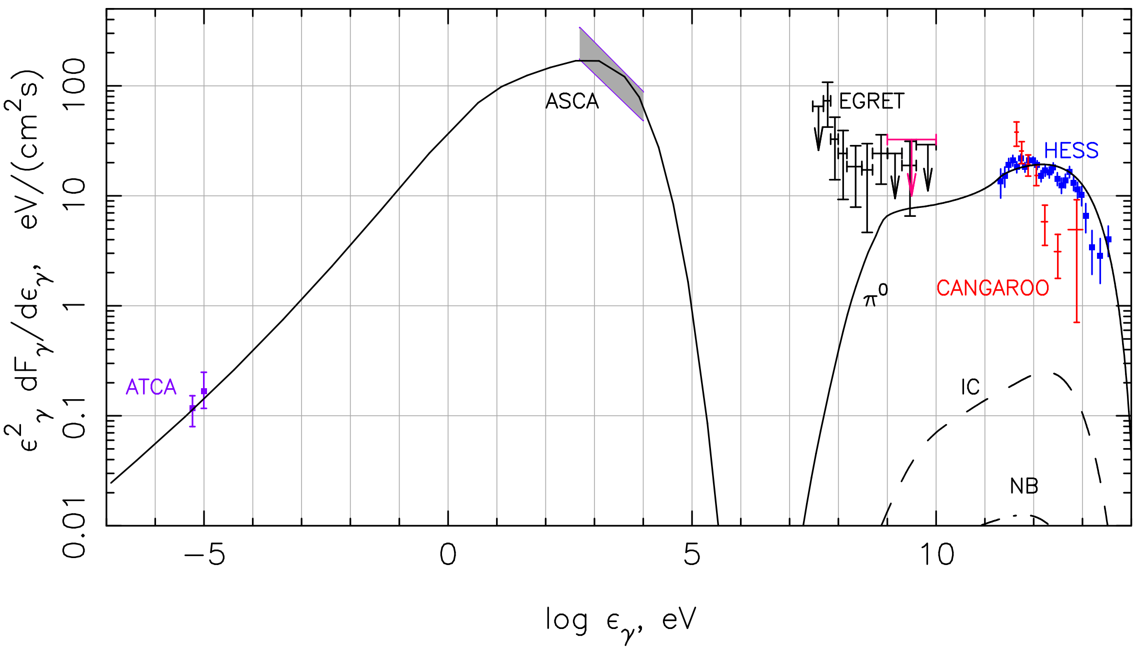

Figure 1: Spatially integrated spectral energy distributions of RX J1713-3946 [6]. The ATCA radio data, ASCA X-ray data, EGRET spectrum of 3EG J1714-3857, CANGAROO data and H.E.S.S. data from ([5]), are shown, together with the EGRET upper limit for the H.E.S.S. source position. The solid curve at energies above 10^7 eV corresponds to π^0-decay γ-ray emission, whereas the dashed and dash-dotted curves indicate the inverse Compton (IC) and Nonthermal Bremsstrahlung (NB) emissions, respectively.

derive – from synchrotron spectral observations – two determining physical quantities: the effective strength of the magnetic field and the proton injection rate into the diffusive acceleration process. Strictly speaking, it is therefore not possible to theoretically predict the TeV γ-ray emission. BV06 argue nevertheless that the observed overall synchrotron spectral shape, from radio frequencies to the X-ray cutoff, and the small-scale filamentary structures in the nonthermal X-ray emission of RX J1713-3946 are consistent with efficient CR acceleration associated with a considerably amplified magnetic field. These properties allow in addition a consistent fit of the observed TeV γ-ray spectrum. It is strongly dominated by π^0-decay emission [5].

Model

For a present angular radius of the SNR of 60', at the adopted distance of $d = 1$ kpc the linear remnant radius corresponds to 10 pc. To produce the high observed γ-ray flux the SN shock must already propagate into the increasing density $N_{\rm H}$ of the shell of swept-up ambient interstellar medium (ISM) whereas the high nonthermal X-ray emission in the energy range of several keV requires a presently still high shock speed $V_s \approx 1840$ km/s, and therefore a very low bubble density $N_b \approx 10^{-2}$ cm^{-3}. This requires an ISM density $N_{ISM} = 300$ cm^{-3}, i.e. a bubble in a molecular cloud. A consistent hydrodynamic explosion energy is $E_{sn} = 1.8 \times 10^{51}$ erg, with an ejected mass of $M_{\rm ej} = 3.5\ M_\odot$ which give a swept-up mass $M_{sw} \approx 20 M_\odot \gg M_{\rm ej}$, already at the present time.

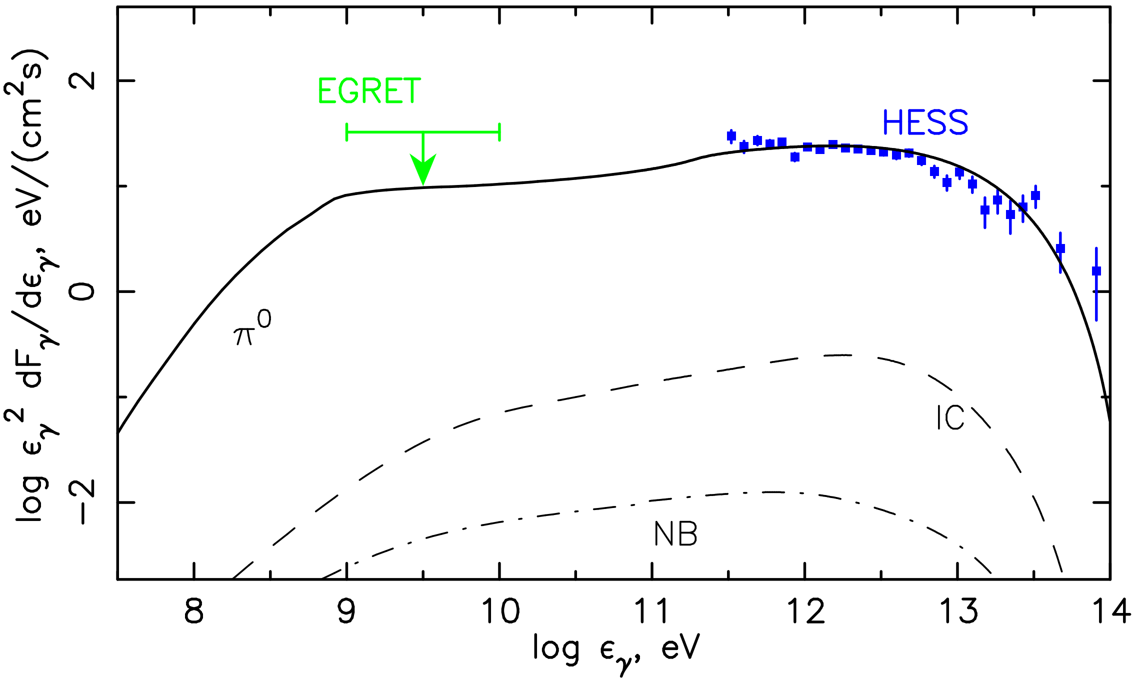

Figure 2: The same theoretical spectra above 10^7 eV as in Fig.1, on an expanded scale, together with the EGRET upper limit for the H.E.S.S. source position and with the latest H.E.S.S. spectrum from [13].

The effective magnetic field strength B inside the SNR, taken as approximately uniform [14], determines the strength and form of the electron distribution for given observed synchrotron emission strength, and thus also the inverse Compton emission at very high γ-ray energies for a given radiation field like the CMB. Since the spatially integrated radio synchrotron spectrum is not known in detail, B is determined using the existence of narrow filaments in hard X-rays, whose thickness we interpret as the result of synchrotron losses of the highest-energy electrons behind the SNR shock. Recent XMM observations by Hiraga et al. [15] show such a narrow filament from which BV06 derived a lower limit to the interior field strength of $B = 65\mu$G. It is clearly amplified relative to the field strength in the ambient shell and indicates effective acceleration of nuclear particles [16]. The actual value used in the model for the synchrotron emission is $\approx 130\mu$G.

Results and discussion

The amplitude of the observed VHE γ-ray emission can be fitted with a proton injection rate $\eta = 3 \times 10^{-4}$, quite plausible from theoretical considerations. This is consistent with the high B-field strength which implies a predominantly hadronic γ-ray emission, since the leptonic channel is strongly suppressed for the given synchrotron emission. The overall shock compression ratio is $\sigma = 6.3$, i.e. the shock is significantly modified by the accelerated CR protons. It turns out also that our spherically symmetric acceleration model overproduces nonthermal particle energy E_{c}. The necessary deviation of the SNR from spherical symmetry requires a renormalization $f_{re}E_{\mathrm{c}}$ with $f_{re} \approx 0.2$, as for a similar object like Cas A.

Our resulting overall nonthermal spectrum [6] is given in Fig.1. In the VHE range it shows the data from CANGAROO [3], together wih the H.E.S.S. data [5] available at the time. The same theoretical γ-ray spectral energy distribution is compared in Fig. 2 with the latest H.E.S.S. measurements [13] which have significantly increased statistics and energy coverage. Despite the fact that the theoretical model does not contain any particle escape at the highest energies, the spectrum falls off more quickly with energy than the measurement. We trace this back to the fact that the model of BV06 has – in a conservative sense – used the present value of B as a constant value for B during SNR evolution, whereas $B^2/(8\pi)$ presumably scales $\propto N_H V_s^2$ [14, 17] or even $\propto N_H V_s^3$ [16]. These latter scalings would lead to a somewhat higher proton cutoff energy at the present epoch.

Also the theoretical X-ray and TeV γ-ray morphology can be studied. As expected from the filament observations, the projected radial X-ray profile is very narrow. The corresponding profile at 1 TeV is again very narrow, since in particular the gas density has a large radial gradient. Smoothed to the resolution of H.E.S.S., the profile is consistent with the observed H.E.S.S. profile.

A major result remains the hadronic dominance in the γ-ray emission spectrum. We expect that the GLAST instrument will confirm our corresponding theoretical prediction that the spatially integrated γ-ray spectral energy density at 1 GeV is only a factor ≈ 2.5 lower than at 1 TeV.

Acknowledgements

EGB acknowledges the hospitality of the Max-Plank-Institut für Kernphysik where part of this work was carried out. This work has been supported by the Russian Foundation for Basic Research (grants 05-02-16412, 06-02-96008, 07-02-0221).

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