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 255–258

ID 597

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Theory of cosmic ray and γ-ray production in the supernova remnant RX J0852.0-4622 (Vela Jr.)

E.G. BEREZHKO[1], G. PÜHLHOFER[2], AND H.J. VÖLK[3].
[1]*Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677980 Yakutsk, Russia*
[2] *Landessternwarte, Königstuhl, 69117 Heidelberg, Germany*
[3]*Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany*
berezhko@ikfia.ysn.ru

Abstract: Explicitly time-dependent, nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) has been used to investigate the properties of the very large SNR RX J0852.0-4622. The available observations do not clearly distinguish between a "nearby" (at $\sim$ 200 pc) and a "distant" (at $\sim$ 1 kpc) source scenario. Therefore two correspondingly different models were analyzed. While the 200 pc solution can not be a priory excluded, the 1 kpc solution turns out to be clearly preferable for physical reasons. It requires a core collapse supernova (SN) with a massive progenitor in a molecular cloud $\sim$ 4000 yrs ago. The overall synchrotron spectrum and the filamentary structures in hard X-rays both consistently lead to an amplified magnetic field $B > 100\mu$G in the SNR interior. This implies a suppression of the leptonic TeV γ-ray emission to about 1 percent of the flux measured by the H.E.S.S. telescope system which therefore must be hadronic, consistent with the theoretical solution. Up to the present the 1 kpc solution has already converted $\sim$ 10 percent of the explosion energy into nonthermal energy, as expected for a Galactic CR source. Also the derived γ-ray morphology is consistent with the H.E.S.S. measurements. For the "nearby" solution the leptonic and hadronic γ ray fluxes are in the ratio 1:10 which means that this case is also hadronically dominated. However, the magnetic field strength, consistent with the overall synchrotron spectrum, differs significantly from that derived from the X-ray filaments. Finally, the total mechanical energy released amounts to only 1.8×10^{50} erg, uncomfortably low even for a core collapse event.

Introduction

RX J0852.0-4622 (often, and also here, called Vela Jr.) is a shell-type supernova remnant (SNR) with a diameter of 2°, located in the Galactic plane. It was originally discovered in X-rays with ROSAT [1]. In projection Vela Jr. lies entirely within the still much larger Vela SNR and is only visible in hard X-rays, where the thermal radiation from the Vela SNR is no longer dominant. We note that, regarding its size and complexity, Vela Jr. has similarities with the X-ray SNR RX J1713.7-3946 also detected in VHE γ-ray observations (e.g. [2]). The theoretical analysis of Vela Jr., summarized below, will also be similar to that for SNR RX J1713.7-3946 by [3], and we refer to that paper for more detailed arguments and references.

The radio emission of Vela Jr. is weak. Only for the northeastern rim a spectral index can be derived with quite moderate accuracy [4]. Vela Jr. was also detected in very high energy (VHE) γ-rays by the H.E.S.S. collaboration, at the same flux level as the Crab Nebula, and its morphology was resolved as a rather circular shell, e.g. [5]. Emission from the northwestern rim had been detected already before by the CANGAROO experiment, e.g. [6].

The fairly regular shell-type characteristics of this source have prompted us to construct a model of the acceleration of both electrons and protons in detail using an explicitly time-dependent nonlinear kinetic theory of cosmic ray (CR) acceleration that assumes spherical symmetry [7, 8]. We emphasize nevertheless that particle injection is not spherically symmetric which requires a renormalization of the CR energy [9]. The theory couples particle acceleration on a kinetic level with the gas dynamical evolution of the system in the aftermath of the SN explosion. However, the present uncertainties regarding this source are too large as to permit the a priory-assumption of a unique model. Such important astronomical parameters as the distance, expansion speed, age, and explosion type are poorly known. It is not even clear, whether the source is in front or behind the Vela SNR which itself is generally considered to lie at a distance $d = 250 \pm 30$ pc [10]. This led us to consider the construction of two quite different source scenarios. They correspond to earlier distance estimates: a "nearby " solution with $d = 200$ pc [1], and a "distant" solution with $d = 1$ kpc [11]. To rather different degrees of success these constructions turn out to be indeed possible. The SNR ages correspond to $t = 1360$ yr and $t = 3930$ yr, respectively.

We shall argue that – for the favored "distant" solution – the observed nonthermal emission of Vela Jr. indicates that the SNR emerged from a type II SN explosion into the adiabatic wind bubble of a massive progenitor star. In this case the major part of the swept-up volume is occupied by the diluted bubble gas. At the current epoch, however, the SNR shock already propagates into the increasingly dense shell of ambient interstellar medium (ISM) which has originally been compressed by the stellar wind. A "nearby" scenario, on the other hand, is only possible for a uniform ambient medium.

Results

"Distant" solution

For the "distant" solution at 1 kpc the present radius of the SNR blast wave is $R_{\rm s} \approx 17.5$ pc. Such a large size, combined with the need for a shock that is presently still fast in order to explain the luminosity in hard X-rays, requires a very low thermal gas density at least in the deeper interior of the remnant. Therefore the progenitor star must have had originally a large mass, somewhat below $20M_{\odot}$, in a surrounding ISM of density $12 < N_{\rm ISM} < 40$ cm^{-3}, i.e. in a molecular cloud. Consistent values for total mechanical energy release and ejected mass are $E_{\rm sn} = 2 \times 10^{51}$ erg and $M_{\rm ej} = 3.5M_{\odot}$, respectively. The effective magnetic field strength B inside the remnant should be both consistent with the observation of thin X-ray filaments with the Chandra telescope [12], from

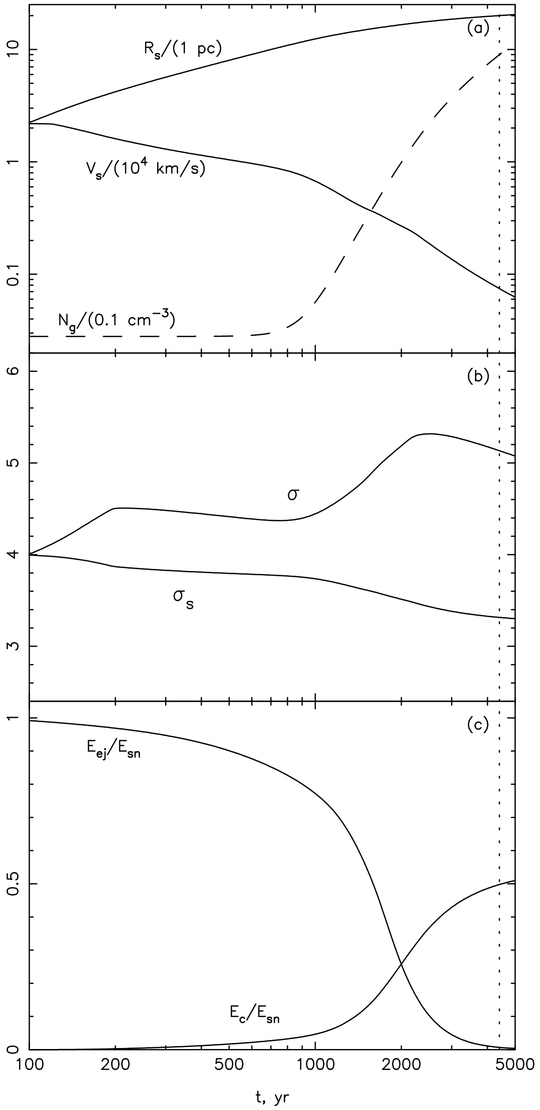

Figure 1: Calculated hydrodynamic quantities for the distanse $d = 1$ kpc. (a) Shock radius $R_{\rm s}$, velocity $V_{\rm s}$, and gas density $N_{\rm g}$ as functions of time; (b) Total (σ) and subshock ($\sigma_{\rm s}$) compression ratio; (c) ejecta energy ($E_{\rm ej}$) and CR energy ($E_{\rm c}$), where the latter has still to be renormalized on account of the lack of spherical symmetry. The vertical dotted lines mark the current epoch of SNR evolution.

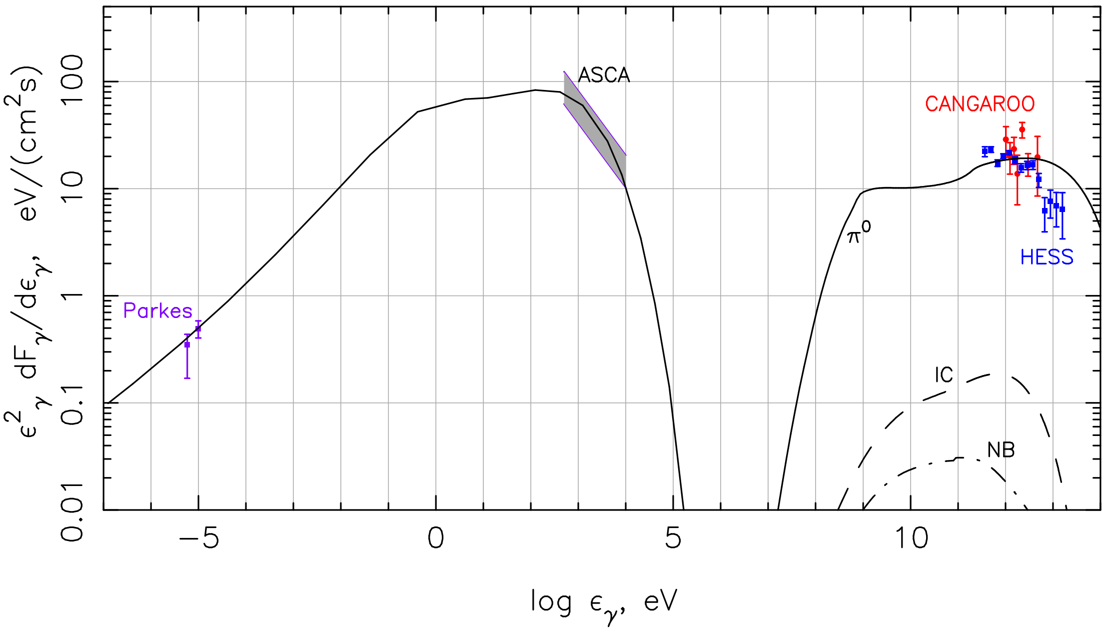

Figure 2: Calculated spectral energy distribution for Vela Jr. for the 1 kpc solution as function of photon energy. In the γ-ray region the solid curve shows the π^0-decay emission, whereas the dashed and the dash-dotted lines denote the inverse Compton and nonthermal Bremsstrahlung emissions, respectively. Radio [4] and X-ray synchrotron fluxes [11, 5], CANGAROO [6] and H.E.S.S. [5] TeV data are also shown.

which we derive a present-day value $B \approx 130\mu$G, as well as with the form of the overall, spatially integrated synchrotron spectrum. To fit the latter we used a value $B = 106\mu$G – constant in time – in satisfactory agreement with the filament value. This shows that the magnetic field is significantly amplified compared to the value upstream of the shock, and this is only possible through an effectively accelerated nuclear CR component. The large B-field at the same time suppresses the accelerated CR electron component. To obtain the amplitude of the observed γ-ray spectrum a – theoretically quite plausible – proton injection rate $\eta = 3 \times 10^{-4}$ is required.

This model and its parameters allow a reasonable fit for the present hydrodynamical variables like shock radius R_s, shock velocity $V_\text{s} = 750$ km/s, compression ratio and overall CR energy (Fig.1). We note that at early times $V_\text{s} \approx 20.000$ km/s is quite large and the (central) gas density ($N_\text{g} \approx 0.003$ cm^{-3} very low, whereas in the swept-up shell of molecular cloud gas the shock has finally strongly decelerated, being already far beyond sweep-up. Not taking escape of the highest energy particles into account over this recent phase, the maximum proton energies are $p_\text{max} \approx 7 \times 10^5$ GeV. Had we taken an effective B-field strength $\propto (N_\text{g}V_s)^{1/2}$, with the above value characterizing the present epoch, then the maximum momentum would be even higher. The spectral energy density (Fig. 2) for the 1 kpc model is characterized by a “flat-top” synchrotron peak due to synchrotron cooling, together with a hadronic dominance of the γ-ray emission spectrum by roughly two orders of magnitude. The synchrotron losses as a result of the amplified B-field permit a good fit to the X-ray data. The gamma-ray data can be understood in terms of particle escape, despite the fact that the magnetic field value was taken constant during SNR evolution. Otherwise the discrepancy in the cutoff energy would be even somewhat greater. Disregarding this difficulty for the moment, the hadronic dominance is a robust result, based not only on the synchrotron spectrum but on the X-ray morphology as well. The (renormalized) energy in nonthermal particles at the present epoch

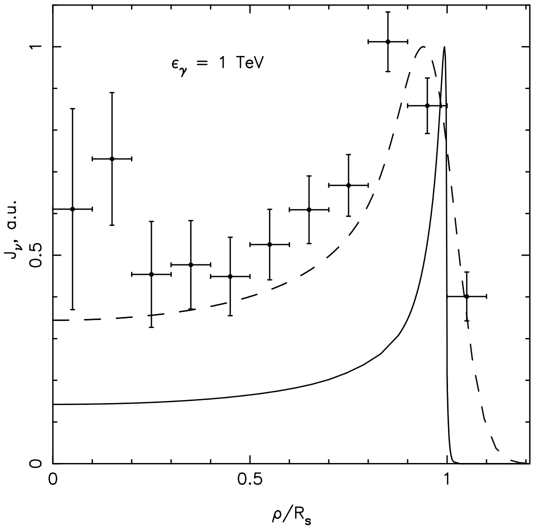

Figure 3: The γ-ray emissivity for the energy $\epsilon_\gamma = 1$ TeV as function of projected, normalized radial distance ρ/R_s for the "distant" solution. The calculated radial profile is represented by the solid line. Data points are from the Northern part of Vela Jr. [5], with an analysis point spread function of Gaussian width 0.06°. The dashed line represents the calculated profile convolved with the same point spread function.

amounts to ≈ 10 percent of the total mechanical energy $E_\mathrm{sn} = 2 \times 10^{51}$ erg released in the SN explosion. Therefore from the point of view of energetics this solution for Vela Jr. fulfills the average requirement on a SNR source of the Galactic CRs.

The γ-ray shell morphology at TeV energies with an observed center-to-limb intensity ratio of ~ 0.35, also agrees reasonably well with the model (Fig.3), given the limited angular resolution of the instrument, and ignoring the two data points in the central region as possibly due to a central SNR component. It is worthwhile to comment that the inferred spherically symmetric 3-dim. thickness of the γ-ray shell is much smaller and corresponds to only about 1 percent of the shock radius!

"Nearby" solution

The "nearby" solution represents a much earlier stage of SNR evolution. Although it cannot be excluded right away, the spectrum and the morphology in the TeV γ-ray region can only be fitted with more liberal criteria. Also the magnetic field strengths, derived from the filamentary X-ray morphology on the one hand, and on the overall synchrotron spectrum on the other, differ significantly. Finally, the total mechanical energy release $E_\mathrm{sn} \approx 1.8 \times 10^{50}$ erg is uncomfortably low, even though this may not be impossible [13]. In conclusion, everything argues for the "distant" solution. A strict empirical proof in favor of this solution would come from observations of the true distance of the SNR. The hadronic dominance of the γ-ray emission is, however, independent of either one of these locations of the source.

This work has been supported by the Russian Foundation for Basic Research (grants 05-02-16412, 06-02-96008, 07-02-0221).

References

[1] B. Aschenbach. *Nature*, 396:141, 1998.

[2] F.A. Aharonian et al. (HESS Collaboration). *Astron. Astrophys.*, 449:223, 2006.

[3] E.B. Berezhko and H.J. Völk. *Astron. Astroph.*, 451:981–990, 2006.

[4] A.R. Duncan and D.A. Green. *Astron. Astrophys.*, 364:732, 2000.

[5] F.A. Aharonian et al. (HESS Collaboration). *Astrophys. J.*, 661:236–249, 2007.

[6] R. Enomoto et al. *Astrophys. J.*, 652:1268, 2006.

[7] E.B. Berezhko et al. *JETPh.*, 82:1, 1996.

[8] E.B. Berezhko and H.J. Völk. *Astron. Astrophys.*, 375:183, 2000.

[9] H.J. Völk et al. *Astron. Astrophys.*, 409:536, 2003.

[10] A.N. Cha et al. *Astrophys. J.*, 515:L25, 1999.

[11] P. Slane et al. *Astrophys. J*, 548:814, 2001.

[12] A. Bamba et al. *Astrophys. J.*, 632:294, 2005.

[13] A. Pastorello et al. *MNRAS*, 347:74–94, 2004.