Cosmic ray acceleration parameters from multi-wavelength observations. The case of SN 1006

E.G. Berezhko*, L.T. Ksenofontov* and H.J. Völk†

*Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677980 Yakutsk, Russia
†Max Planck Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany

***Abstract*. The properties of the Galactic supernova remnant (SNR) SN 1006 are theoretically reanalysed. We use nonlinear kinetic theory to determine the acceleration efficiency of cosmic rays (CRs) in the supernova remnant SN 1006. The known range of astronomical parameters and the existing measurements of nonthermal emission are examined in order to define the values of the relevant physical parameters which determine the CR acceleration efficiency. It is shown that the parameter values – proton injection rate, electron to proton ratio and downstream magnetic field strength –are determined with the appropriate accuracy. These parameters, provide a good fit to the existing data, including the recently detected TeV emission by H.E.S.S. SN 1006 represents the first example where a high efficiency of CR production, required for the Galactic CR sources, is consistently established.**

***Keywords*: ISM: cosmic rays – acceleration of particles – shock waves – stars: supernovae: individual: SN 1006 – radiation: emission mechanisms: nonthermal– gamma-rays: theory**

I. Introduction

Cosmic rays (CRs) below the energy 10^{17} eV are believed to be accelerated in the shell-type supernova remnants (SNRs) of our Galaxy, e.g. [1]. However, this proposition has still only a limited observational/theoretical basis. To ensure that Galactic SNRs are indeed the main sources of the Galactic CRs one needs to have a number of SNRs with clearly determined astronomical parameters, like the type of supernova explosion, the SNR age, the distance, and the properties of the circumstellar medium. Applying to such SNRs an appropriate model which consistently describes the dynamics of the SNR, one can predict the properties of the accelerated particles and all dynamical and radiative effects which they produce, like the shock modification and the multi-wavelength nonthermal emission.

The success of the theoretical model is judged by comparison with the experimentally determined overall broad band spectrum and with the morphological characteristics of the SNR, like its filament structures and the general radial and azimuthal variations of the emission pattern, as well as the internal dynamics characterized by the contact discontinuity between ejected and swept-up mass. From the point of view of Galactic CR origin, the key quantity is the efficiency of CR production.

In practice such a program is usually hampered by the limited amount and detail of relevant observations. First of all, the astronomical parameters of SNRs are as a rule poorly known. Even though the SNR age is known for several historical SNRs, the distance is usually quite uncertain. In this regard SN 1006 is an exception: the distance was determined using optical measurements with relatively high precision [2].

The other problem is that even the presently most advanced nonlinear kinetic theory of CR acceleration in SNRs [3], [4] contains physical parameters which can not yet be theoretically calculated with the necessary precision, e.g. [5]. This concerns the magnitude and the spatial distribution of the injection rates of ions and of electrons into the diffusive shock acceleration process as well as the extent of magnetic field amplification in this process. Fortunately, the values of these parameters can be inferred from the observed radio and X-ray synchrotron spectra if they are measured in sufficient detail, e.g. [6], [7]. In such a case this theory provides a consistent if still approximate description of both SNR and CR dynamics, and the properties of the emission produced by the accelerated particles. In particular, the theory predicts the high-energy γ-ray spectrum.

Up to now SN 1006 is the only example, for which all astronomical parameters are quite well known, e.g. [8]. It was already shown [9] with the then available empirical knowledge that nonlinear kinetic theory is consistent with all observational data, including the H.E.S.S. upper limit of the Very High Energy (VHE:above 100 GeV) γ-ray emission. In the meantime the nonthermal emission in the radio and X-ray bands has been measured quite accurately with Chandra [10] and Suzaku [11]. Beyond that, the VHE emission of SN 1006 has been recently detected with H.E.S.S., both regarding its flux and its morphology [13]. This makes SN 1006 even more suitable for theoretical study and for a detailed comparison with the experimental data.

In this paper we shall demonstrate that the values of the relevant physical parameters are determined for SN 1006 with appropriate accuracy from the measured synchrotron spectrum.

II. Results and discussion

Since SN 1006 is a type Ia supernova it presumably expands into a uniform ISM, ejecting roughly a Chandrasekhar mass $M_{\rm ej} = 1.4 M_{\odot}$. Since the gas density indeed varies only mildly across the SNR [14], it appears reasonable to assume also the circumstellar magnetic field to be uniform. The ISM mass density $\rho_0 = 1.4 m_\mathrm{p} N_\mathrm{H}$, which is usually characterized by the hydrogen number density N_H, is an important parameter which strongly influences the expected SNR dynamics and nonthermal emission.

The values of the SN explosion energy $E_\mathrm{sn} = 1.8 \times 10^{51}$ erg and $E_\mathrm{sn} = 1.5 \times 10^{51}$ erg were taken to fit the observed shock size R_s and shock speed V_s [15] at the current epoch $t \approx 10^3$ yr for the ISM number densities $N_\mathrm{H} = 0.05$ cm^{-3} and $N_\mathrm{H} = 0.035$ cm^{-3}, respectively. These densities are consistent with the observed level of the VHE emission (see below).

We shall take as the most reliable estimate for the distance $d = 2.2$ kpc [2].

As in our earlier study [9] we apply here nonlinear kinetic theory of CR acceleration in SNRs to find the optimum set of physical parameters of SN 1006 which gives a consistent description of the observed overall dynamics and of the nonthermal emission together with its morphology. The theory includes all the important physical factors which influence CR acceleration and SNR dynamics: shock modification by CR backreaction, MHD wave damping within the shock transition, a consistently determined CR spectrum, and the spatial distributions in each evolutionary phase. In addition it includes synchrotron losses of CR electrons and a determination of all nonthermal emission processes, produced in SNRs by the accelerated CRs. It had also been shown that the values of these key parameters (proton injection rate η, electron to proton ratio K_ep and interior (downstream) magnetic field strength B_d) which can not be predicted theoretically with the required accuracy, can be determined from a fit of the observed synchrotron emission data. It is of basic importance here that the parameter values for SN 1006, determined in this way, were very well confirmed by the Chandra measurements of the fine structure of the nonthermal X-ray emission [16], [17], as analyzed by [18], [19]. Compared with our previous study [9] we include in the analysis the most accurate X-ray data of Chandra [10] and Suzaku [11], that make it possible to quite precisely determine the acceptable range of these parameter values. Since we are not interested in the escaping particles in this context, B_0 is taken as time-independent.

Fig. 1 and 2 illustrate the consistency of the synchrotron spectrum, calculated with the best set of parameters ($\eta = 3\times10^{-4}$, $K_\mathrm{ep} = 4\times10^{-4}$, $B_0 = 30$ μG) with the observed spatially integrated spectra. Here we define $B_0 \equiv B_\mathrm{d}/\sigma$, where σ is the overall shock compression ratio. In this sense B_0 is a measure of the magnetic field amplification in the upstream precursor.

We note that the values $\alpha > 0.5$ of the radio spectral index $\alpha = -d \ln S_\nu / d \ln \nu$, as observed in young SNRs, require a curved electron spectrum that hardens to higher energies as predicted by nonlinear shock acceleration models. To have $\alpha = 0.57$ in the radio range, as observed for SN 1006, one needs efficient CR acceleration

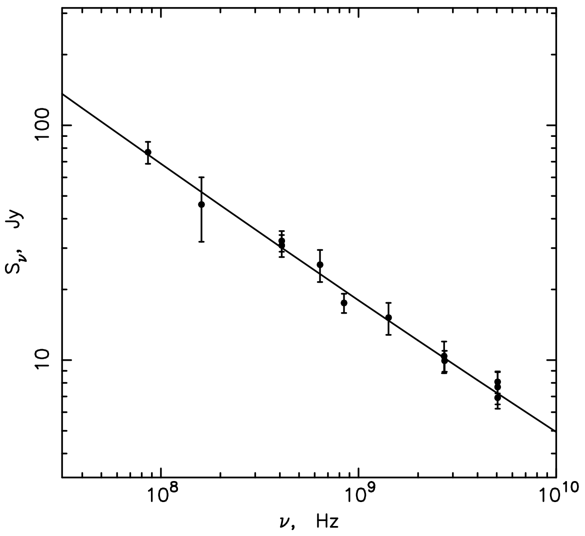

Fig. 1. Synchrotron radio emission flux as a function of frequency, calculated at the proton injection rate $\eta = 3\times10^{-4}$, electron to proton ratio, $K_\mathrm{ep} = 4 \times 10^{-4}$, and magnetic field strength $B_0 = 30$ μG upstream of the subshock . The observed radio emission flux from a compilation of [10] (see also [20]) is shown.

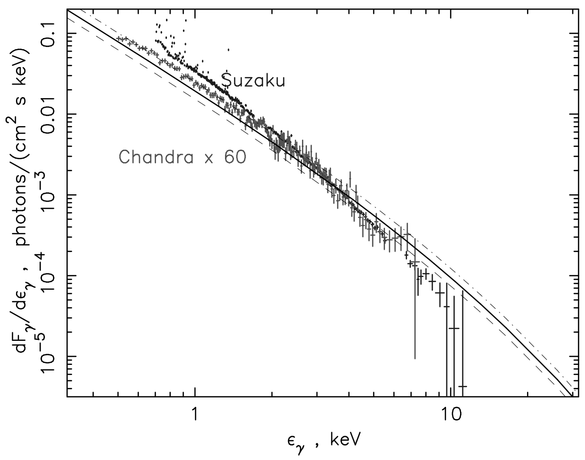

Fig. 2. X-ray synchrotron emission flux as a function of photon energy for the same case as in Fig.1 (solid line). Calculations for $B_0 = 27$ μG (*dashed line*) and for $B_0 = 33$ μG (*dash-dotted line*) are also presented. The observed X-ray flux from Chandra for a small region of the bright eastern rim of SN 1006 [10], and the global X-ray spectrum as observed by Suzaku [11] are shown. The Chandra X-ray flux was normalized such as to be consistent with the Suzaku flux for energies $\epsilon > 3$ keV.

with a proton injection rate $\eta = 3 \times 10^{-4}$ which leads to the required shock modification, and also leads to a high interior magnetic field $B_\mathrm{d} \geq 130$ μG. Detailed X-ray synchrotron spectral measurements are, however, required to find the optimum value of the magnetic field strength B_d [9]: for a given fit of the synchrotron spectrum in the radio range the X-ray synchrotron amplitude is very sensitive to B_d. We note that the synchrotron spectrum is almost insensitive to the ISM density N_H e.g. [9].

To obtain the fit to the data shown in Fig. 1 and Fig. 2 we have asserted that only the highest energy part of the observed global X-ray spectrum, corresponding

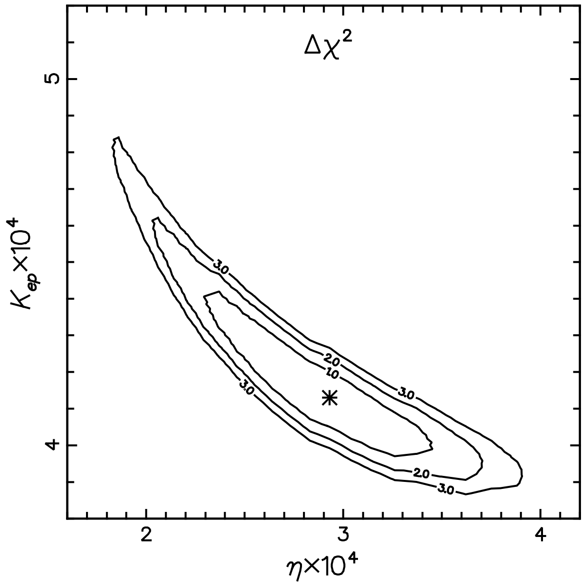

Fig. 3. Contours of equal values of χ^2, corresponding to the successive increase $\Delta\chi^2 = 1$, in the plane that is spanned by the electron to proton ratio $K_{\rm ep}$ and the proton injection rate η. The asterisk corresponds to the best fit values $\eta = 3 \times 10^{-4}$ and $K_{\rm ep} = 4 \times 10^{-4}$ with $\chi^2/{\rm dof} = 1.3$.

to $\epsilon > 2$ keV, is of predominantly nonthermal origin. Towards lower energies $\epsilon < 2$ keV the contribution of thermal emission to this X-ray spectrum progressively increases. Therefore we use for our consideration the X-ray Chandra flux from a small region of the bright north eastern rim of SN 1006 [10], where the contributions from thermal X-rays are presumably negligible compared with other remnant regions [10], [8]. In order to apply it to the whole remnant, this X-ray flux was normalized to be consistent at energies $\epsilon > 2$ keV with the global X-ray spectrum as observed by Suzaku [11]. This consistency in fact exists.

Comparison with the experimental X-ray data shows in Figs. 1 and 2 that the optimum magnetic field value is $B_0 = 30$ μG, and corresponds to a downstream field $B_{\rm d} \approx 150$ μG. This is in agreement with the field amplification that is implied by the filamentary structures in hard X-rays [12].

The quality of fit of the radio spectrum, and of the X-ray spectra for $\epsilon > 2$ keV, for $B_0 = 30$ μG is characterised by the value $\chi^2/{\rm dof} = 1.3$. A change of the magnetic field strength value by only 10 % leads to an increase of χ^2 by ≈ 1.

In Fig. 3, we the present the contours of χ^2 characterizing the quality of fit of the radio spectrum, and of the X-ray spectrum for $\epsilon > 2$ keV, for different values of η and $K_{\rm ep}$. One can see that the quality of the fit is rather good, allowing only a rather small range of these parameters.

The γ-ray morphology, as found in the H.E.S.S. measurements [13], is consistent with the prediction of a polar cap geometry by [21]. Such a geometry has been also found experimentally from an analysis of the synchrotron morphology in hard X-rays by [22] and [8]. This means that the γ-ray emission calculated in our spherically symmetric model must be renormalized (reduced) by a factor $f_{\rm re} \approx 0.2$, as in [9]. We apply this renormalization factor here.

This morphology is also a key argument for the existence of an energetically dominant nuclear CR component in SN 1006, because only such a component can amplify the magnetic field to the observed degree. If on the contrary the existing energetic electron component would have to drive the magnetic field amplification all by itself then we would, as a minimum, require $P_{\rm e} \gg B_0^2/(8\pi)$, where $P_{\rm e}$ is the pressure of CR electrons at the shock front. Clearly $P_{\rm e} \lesssim K_{\rm ep} P_{\rm p}$, where $P_{\rm p}$ is the pressure of CR protons. Since $P_{\rm p} \approx 0.5\rho_0 V_{\rm s}^2$ we have $P_{\rm e} \approx 0.07 B_0^2/(8\pi)$ for $N_{\rm H} = 0.05$ cm^{-3} and $V_{\rm s} \approx 4000$ km/s. Therefore accelerated electrons are unable to amplify the magnetic field to the required level. On the other hand, an effectively accelerated nuclear component has the pressure $P_{\rm p} \approx 200 B_0^2/(8\pi)$ and can therefore readily amplify the field from a purely energetic point of view.

The amplified field must also be the reason for the corresponding polar cap-type morphology of the synchrotron emission in hard X-rays. Even though the weak radio synchrotron emission all around the periphery of SN 1006 [22], [8] demonstrates that electrons are injected essentially everywhere into the acceleration process over the shock, they reach the multi-TeV energies for X-ray synchrotron emission only in the polar caps, where the amplified field allows their acceleration to these energies.

The only important parameter which can not be determined from the analysis of the synchrotron emission data is the external density $N_{\rm H}$. Therefore we have performed the calculations for the pair of values $N_{\rm H} = 0.05$ cm^{-3} and $N_{\rm H} = 0.035$ cm^{-3} which seems to bracket the density range consistent with the H.E.S.S. γ-ray measurements.

Fig. 4 shows the total (π^0-decay plus inverse Compton (IC)) and the IC γ-ray energy spectra of the remnant, calculated for $N_{\rm H} = 0.05$ cm^{-3} and $N_{\rm H} = 0.035$ cm^{-3}.

H.E.S.S. has reported the measured value of the energy flux $\Phi(\epsilon_1, \epsilon_2) = 2.5 \times 10^{-12}$ erg/(cm^2 s) of γ-rays with energies $\epsilon_1 \le \epsilon_\gamma \le \epsilon_2$ where $\epsilon_1 = 0.2$ TeV and $\epsilon_2 = 40$ TeV. It is related with the differential γ-ray energy spectrum according to the expression

$$\Phi(\epsilon_1, \epsilon_2) = \int_{\epsilon_1}^{\epsilon_2} \epsilon_\gamma^2 \frac{dF_\gamma}{d\epsilon_\gamma} d\ln\epsilon_\gamma = \ln\frac{\epsilon_2}{\epsilon_1} < \epsilon^2 \frac{dF_\gamma}{d\epsilon} >,$$

which gives the mean experimental value of the differential energy flux $< \epsilon^2 dF_\gamma/d\epsilon >= \Phi(\epsilon_1, \epsilon_2)/\ln(\epsilon_2/\epsilon_1)$, shown in Fig. 4.

According to Fig. 4 the H.E.S.S. data are consistent with an ISM number density from quite a narrow interval $0.03 \le N_{\rm H} \le 0.05$ cm^{-3}, since for our theoretically derived γ-ray spectrum we have $\Phi = 2.1\times10^{-12}$ erg/(cm^2 s) and $\Phi = 2.9\times10^{-12}$ erg/(cm^2 s)

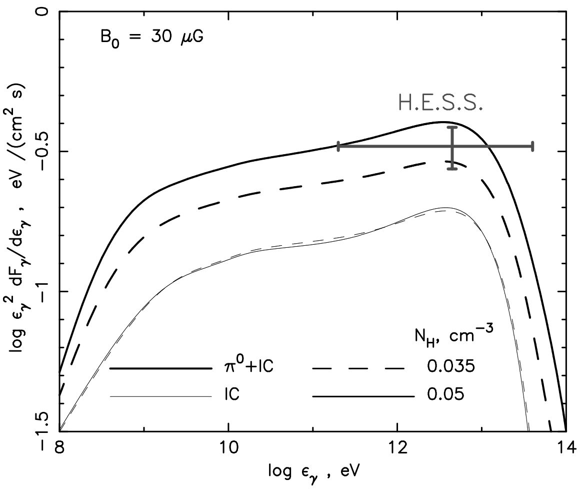

Fig. 4. Total (π^0-decay + IC) (*thick lines*) and IC (*thin lines*) differential γ-ray energy fluxes as a function of γ-ray energy, calculated for ISM hydrogen number densities $N_{\rm H} = 0.05$ cm^{-3} (*solid lines*) and $N_{\rm H} = 0.035$ cm^{-3}. (*dashed lines*). The H.E.S.S. value [13] is shown as well.

for $N_{\rm H} = 0.035$ cm^{-3} and $N_{\rm H} = 0.05$ cm^{-3} respectively. We note that the corresponding explosion energy $E_{\rm sn} \approx 1.7 \times 10^{51}$ erg is close to the upper end of the typical range of type Ia SN explosion energies that vary by a factor of about two [23], [24].

Note also, that [14] find the value $N_{\rm H} \approx 0.05$ cm^{-3} on the basis of X-ray measurements, that is consistent with our interval.

III. Summary

Since the relevant astronomical parameters as well as the synchrotron spectrum of SN 1006 are measured in impressive detail it is possible to determine the values of the relevant physical parameters with the appropriate accuracy for this SNR: proton injection rate $\eta = (2.9 \pm 0.6) \times 10^{-4}$, electron to proton ratio $K_{ep} = (4.1 \pm 0.3) \times 10^{-4}$ and downstream magnetic field strength $B_d = (150 \pm 15)$ μG.

As a result the flux of TeV emission detected by H.E.S.S. is consistent with the ISM number density $0.035 \le N_{\rm H} \le 0.05$ cm^{-3}. The corresponding hydrodynamic SN explosion energy $E_{\rm sn} = 1.7 \times 10^{51}$ erg is close to the upper end $E_{\rm sn} = 1.6 \times 10^{51}$ erg of the typical range of type Ia SN explosion energies that vary by a factor of about two. Also the magnetic field amplification properties of this SNR are well understandable as the result of azimuthal variations of ion injection over the projected SNR circumference and corresponding acceleration which leads to a polar cap-type X-ray synchrotron and γ-ray emission morphology.

In conclusion SN 1006 represents the first example when high efficiency of nuclear CR production, required for the Galactic CR sources, is consistently established.

IV. Acknowledgements

This work has been supported in part by the Russian Foundation for Basic Research (grants 06-02-96008, 07-02-00221), Programm of PRAS No. 16 and by the Leading Scientific Schools of Russia (project 3968.2008.2). The authors are grateful to Drs. Aya Bamba and Glen Allen who provided them with the most recent X-ray data from the Chandra and Suzaku satellite observatories. The authors also thank Dr. Vladimir Zirakashvili for scientific discussions regarding electron acceleration in SN 1006. EGB and LTK acknowledges the hospitality of the Max-Planck-Institut für Kernphysik, where part of this work was carried out.

References

[1] Berezhko, E.G. & Völk, H.J. 2007, ApJ, 661, L175
[2] Winkler, P. F., Gupta, G., & Long, K. S. 2003, ApJ, 585, 324
[3] Berezhko, E. G., Elshin, V. K., & Ksenofontov, L. T. 1996, J. Exp. Theor. Phys., 82, 1
[4] Berezhko, E. G. & Völk, H. J. 1997, Astropar. Phys., 7, 183
[5] Völk, H. J. 2004, in *Frontiers of Cosmic Ray Science*, Proc. 28th ICRC, Tsukuba, 8, 29 ff, ed. T, Kajita, Y. Asaoka, A. Kawachi, Y. Matsubara, & M. Sasaki (Tokyo, Japan, Universal Academy Press Inc.)
[6] Berezhko, E.G. 2005, Adv. Space Res., 35, 1031
[7] Berezhko, E.G. 2008, Adv. Space Res., 41, 429
[8] Cassam-Chenaï, G., Hughes, J.P., Reynoso, E.M. et al. 2008, ApJ, 680, 1180
[9] Ksenofontov, L. T., Berezhko, E. G., & Völk, H. J. 2005, A&A, 443, 973
[10] Allen, G.E., Houck, J.C., & Sturner, S.J. 2004, Adv. Space Res., 33, 440
[11] Bamba, A., Fukazawa, Y., Hiraga, J. S., et al. 2008, PASJ, 60, S153
[12] Völk, H. J., Berezhko, E. G., & Ksenofontov, L. T. 2005, A&A, 433, 229
[13] Naumann-Godo, M. et al. (HESS Collaboration) 2008, in "High Energy Gamma-Ray Astronomy" (Eds. F.A. Aharonian, W. Hofmann, F.M. Rieger), Melville, New York, 2008, AIP Conf. Proc. 1085, p. 304 ff.
[14] Acero, F., Ballet, J., & Decourchelle, A. 2007, A&A, 475, 883
[15] Moffett, D. A., Goss, W. M., & Reynolds, S. P. 1993, Astron.J., 106, 1566
[16] Bamba, A., Yamazaki, R., Ueno, M., & Koyama, K. 2003, ApJ, 589, 827
[17] Long, K.S., Reynolds, S.P., Raymond, J.C., et al. 2003, ApJ, 586, 1162
[18] Berezhko, E. G., Ksenofontov, L. T., & Völk, H. J. 2003, A&A, 412, L11
[19] Berezhko, E. G. & Völk, H. J. 2004, A&A, 419, L27
[20] Allen, G.E., Petre, R. & Goytthelf, E.V. 2001, ApJ, 558, 739
[21] Völk, H. J., Berezhko, E. G., & Ksenofontov, L. T. 2003, A&A, 409, 563
[22] Rothenflug, R., Ballet, J., Dubner, G., et al. 2004, A&A, 425, 121
[23] Gamezo, V. N., Khokhlov, A. M., & Oran, E. S. 2005, ApJ, 623, 337
[24] Blinnikov, S.I., Röpke, F.K. & Sorokina, E.I. 2006, A&A, 453, 229