Inverse Compton gamma-ray models for remnants of Galactic type Ia supernovae ?

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

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

***Abstract*. We theoretically and phenomenologically investigate the question whether the γ-ray emission from the remnants of the type Ia supernovae SN 1006, Tycho's SN and Kepler's SN can be the result of electron acceleration alone. The observed synchrotron spectra of the three remnants are used to determine the average momentum distribution of nonthermal electrons as a function of the assumed magnetic field strength. Then the inverse Compton emission spectrum in the Cosmic Microwave Background photon field is calculated and compared with the existing upper limits for the very high energy γ-ray flux from these sources. It is shown that the expected interstellar magnetic fields substantially overpredict even these γ-ray upper limits. Only rather strongly amplified magnetic fields could be compatible with such low γ-ray fluxes. However this would require a strong component of accelerated nuclear particles. The analysis given appears to eliminate simplistic phenomenological claims in favor of a inverse Compton gamma-ray scenario for these sources.**

***Keywords*: cosmic rays – acceleration of particles – shock waves – supernovae individual (SN 1006, Tycho's SN, Kepler's SN) – radiation mechanisms:nonthermal – gamma-rays:theory**

I. Introduction

The question, whether the very high energy (VHE) ($E_\gamma > 100$ GeV) γ-ray emission of the Galactic supernova remnants (SNRs) implies a sufficiently large production of nuclear cosmic rays (CRs) – of the same order as that required to replenish the Galactic CRs – is one of the key problems addressed by γ-ray astronomy.

Both nuclear charged particles and electrons can be accelerated to achieve nonthermal momentum distributions. The energetic electrons show their presence through synchrotron emission from radio frequencies to hard X-ray energies. They may also interact with diffuse interstellar radiation field photons, like the Cosmic Microwave Background, to produce high energy γ-rays in inverse Compton (IC) collisions. The injection of electrons into the acceleration process is however poorly understood quantitatively. The amplitude factor of the electron momentum distribution is therefore not known from theory. It is typically inferred from the measured synchrotron spectrum produced by the accelerated electrons by assuming a mean strength of the magnetic field.

The question is then, whether the observed γ-ray emission is dominated by nuclear particles through their inelastic, π^0 - producing collisions with thermal gas nuclei.

The investigation of half a dozen of *young* Galactic SNRs (for reviews, see e.g. [1], [2], [3]) has shown that the nuclear CR production is in all cases so high that the Galactic SNRs are viable candidates for the Galactic CR population up to particle energies $\sim 10^{17}$ eV well above the so-called knee in the spectrum [4].

As far as γ-ray observations are concerned, there is a different approach, basically phenomenological. It considers the question, whether and to which extent the hadronic or leptonic origin of the measured γ-ray emission can be decided by favoring either one mechanism at the expense of the other directly from the data.

Here we analyse the spatially integrated synchrotron emission spectrum for the simplest available objects, the remnants of the three young type Ia SNe, observed in VHE γ-rays. Even though only upper limits exist from the HEGRA, H.E.S.S. and CANGAROO experiments for SN 1006 [5], Tycho's SNR [6], and Kepler's SNR [7], [8], they can nevertheless be used to estimate lower limits to the effective mean magnetic field strengths in the SNR that are consistent with the observed spatially-integrated synchrotron spectra. These somewhat naively estimated magnetic fields are then compared to the expectations for these types of SN explosions. The large discrepancies found disfavor leptonic scenarios for these objects.

II. Simple synchrotron and IC modeling of the integrated emission

The expected synchrotron spectral energy density (SED) at distance d from a SNR is given by the expression [9]

$$E^2\frac{dF^{\rm syn}}{dE}=\frac{3\times10^{-21}}{4\pi d^2}\int d^3r\,B_\perp \times\int_0^\infty dp p^2 f_{\rm e}(\vec{r},p)g\left(\frac{E}{h\nu_{\rm c}}\right) \quad (1)$$

in erg/(cm^{2}s), where

$$g(y)=y\int_y^\infty K_{5/3}(y')dy',$$

$K_\mu(y)$ is the modified Bessel function, E is the photon energy, $\nu_{\rm c}=3eB_\perp p^2/[4\pi(m_{\rm e}c)^3]$, and $B_\perp$ is the interior magnetic field component perpendicular to the line of sight.

We shall use here an approximation that averages over the line of sight directions. A precise analytical integration involving Whittacker's function has been given by [10] which is in turn closely approximated by substituting

$$B_\perp = \sqrt{2/3}B_\mathrm{d}, \tag{2}$$

into Eq.(1). Here B_d is the strength of the interior field which results from the MHD-compression of the upstream magnetic field $\vec{B_0}$ and subsequent decompression in the interior (see below).

The spatial integral in Eq.(1) extends over the volume V of the SNR, as given by the observed synchrotron morphology, and the calculated synchrotron SED has to be compared with the observed SED.

Our starting point for a simplified model is the assumption that $B_\perp$ in the form of Eq.(2) can be taken as a weighted mean value $\sqrt{2/3}\langle B_\mathrm{d}\rangle$ out of the spatial integral of Eq.(1). The postshock value of B_d/B_0 is locally between 1 and σ, where $\sigma > 1$ denotes the overall shock compression ratio. Since the interior field strength is lower than the postshock field strength, we have for this mean interior field strength: $\langle B_\mathrm{d}\rangle < \sigma B_0$.

If we investigate the possibility that the accelerated particles are electrons alone – implying a purely leptonic origin of the VHE γ-ray emission – then we have to consider a test particle problem with $\sigma = 4$. In the same sense B_0 should be equal to the strength of the interstellar magnetic field, i.e. equal to a few μG. Values of $B_0 = 3\mu$G and $B_0 = 5\mu$G then imply $3 < \langle B_\mathrm{d}\rangle < 12\mu$G and $5 < \langle B_\mathrm{d}\rangle < 20\mu$G, respectively.

As a second approximation we shall also assume that the volume integral of $f_\mathrm{e}(\vec{r}, p)$ equals the product of V and an electron distribution

$$\int d^3r f_\mathrm{e}(\vec{r}, p) = VAp^{-\alpha} \times \exp(-p/p_\mathrm{max}), \tag{3}$$

in the form of a power law with an exponential cutoff at p_max. The index $\alpha = 4$ again corresponds to a test particle spectrum. For internal magnetic field strengths in excess of 100μG such a model distribution would have to include a high-energy part of the spectrum that is softened by synchrotron losses, see e.g. [11]. However in the present context, that does by assumption not include massive nuclear particle acceleration, such field strengths are not expected to occur.

In this sense the two parameters A and p_max can be approximately fitted from the known radio and X-ray synchrotron data as a function of B_0. In fact, because of the exponential behaviour of the cut-off of the electron momentum distribution the only sensitive parameter turns out to be A. The fact that the observed radio synchrotron spectra are softer than implied by a distribution with $\alpha = 4$ suggests that the pure electron acceleration model, for the sake of argument considered here, is not the physically correct model. However, a pure electron model is necessarily one with $\alpha = 4$, even if it does not optimally fit the *form* of the observed synchrotron spectrum, but rather only its *amplitude*.

Next we calculate the IC SED from these same electrons in the 2.7 K cosmic microwave background (CMB). This γ-ray SED can be written in the form:

$$E^2\frac{dF_\gamma^\mathrm{IC}}{dE} = \frac{E^2 c}{d^2}\int d^3r \int_0^\infty d\epsilon n_\mathrm{ph}(\epsilon) \times \int_{p_\mathrm{min}}^\infty dp p^2 \sigma(\epsilon_\mathrm{e}, E, \epsilon) f_\mathrm{e}(\vec{r}, p) \tag{4}$$

in erg/(cm^{2}s), where [12]

$$\sigma(\epsilon_\mathrm{e}, E, \epsilon) = \frac{3\sigma_\mathrm{T}(m_\mathrm{e}c^2)^2}{4\epsilon\epsilon_\mathrm{e}^2} \times \left[2q\ln q + (1+2q)(1-q) + 0.5\frac{(\Gamma q)^2(1-q)}{1+\Gamma q}\right] \tag{5}$$

is the differential cross section for the up-scattering of a photon with incident energy ϵ to energy E by the elastic collision with an electron of energy ϵ_e,

$$n_\mathrm{ph} = \frac{1}{\pi^2(\hbar c)^3}\frac{\epsilon^2}{\exp(\epsilon/k_\mathrm{B}T) - 1} \tag{6}$$

is the blackbody spectrum of the CMB, $h = 2\pi\hbar$ and k_B are the Planck and Boltzmann constants, respectively, $T = 2.7$ K, $\sigma_\mathrm{T} = 6.65 \times 10^{-25}$ cm^2 is the Thomson cross-section, $q = E/[\Gamma(\epsilon_\mathrm{e} - E)]$, $\Gamma = 4\epsilon\epsilon_\mathrm{e}/(m_\mathrm{e}c^2)^2$, and p_min is the minimal momentum of the electrons, whose energy ϵ_e is determined by the condition $q = 1$.

We neglect here nonthermal Bremsstrahlung emission which turns out to be unimportant for all the cases considered below.

Since the CMB is uniform, we can without further approximation use Eq.(3) to express the γ-ray SED in terms of the parameters A and p_max. The results are given in Fig. 1a for SN 1006, in Fig. 1b for Tycho's and in Fig. 1c for Kepler's SNRs for various values of $\langle B_\mathrm{d}\rangle$.

III. Discussion

It is clear from the outset that the approximate nature of the models used limits the impact of the conclusions to be drawn from these results. On the other hand, most of the arguments that have been used in the past regarding the alternative between a hadronic and a leptonic interpretation of VHE γ-ray results have used such one box approximations. The only alternative would be full time-dependent solutions of the governing system of equations, discussed in the Introduction.

However, with this proviso, the results are surprisingly clear. For all three sources magnetic field strengths B_0 lower or equal to the expected interstellar magnetic fields of $3 - 5\mu$G substantially overpredict even the existing γ-ray upper limits.

For a shock that excites MHD fluctuations only weakly if at all, because of the assumed lack of acceleration of nuclear particles, the interior gas flow will be essentially laminar and adiabatic. Taking into account

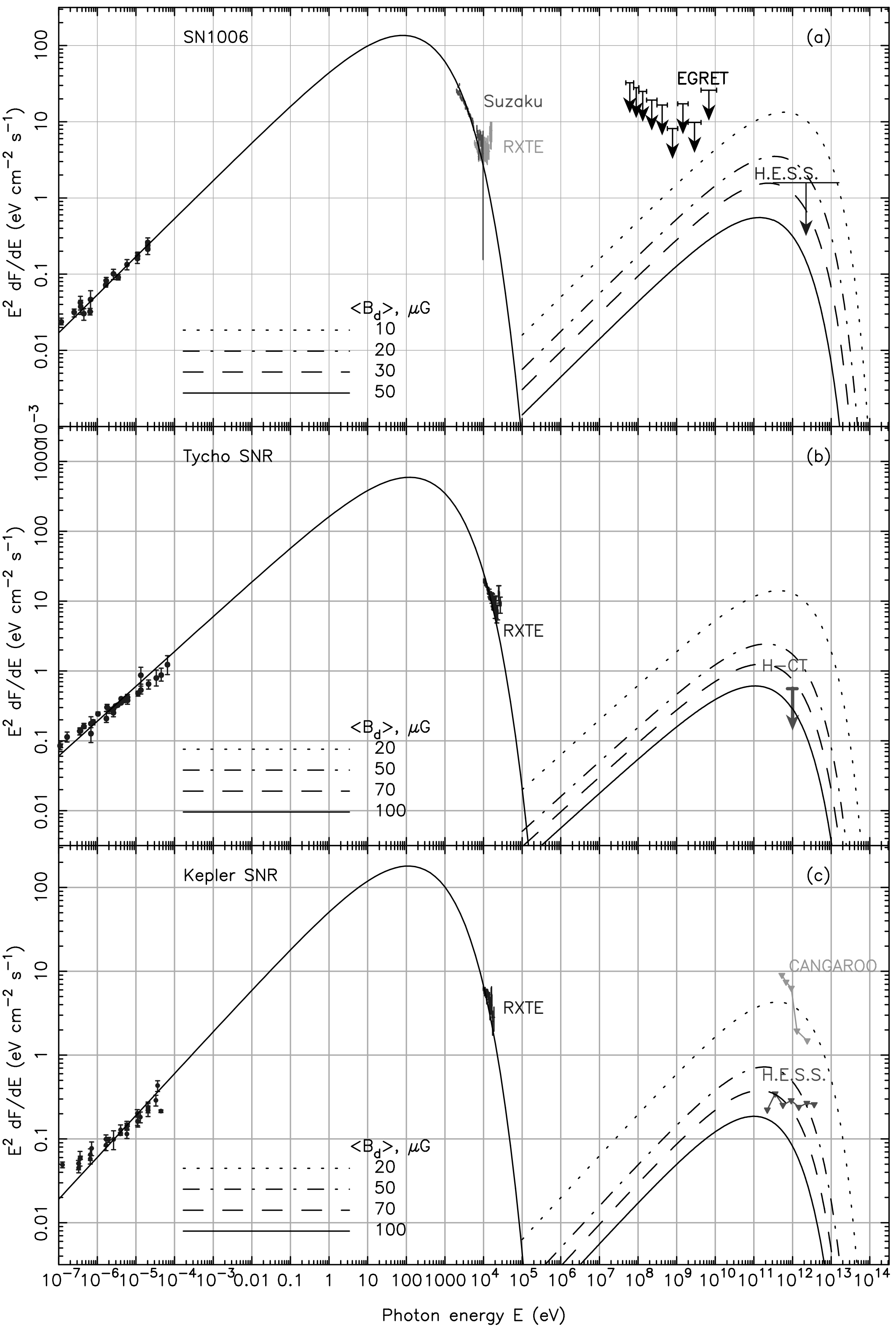

Fig. 1. The overall (spatially integrated) nonthermal spectral energy distribution (SED) as a function of photon energy E. The lower-energy part shows the simple fit to the observed synchrotron-SED, cf. Eq.(3), for various values of the internal field strength $B_\perp$ in μG, cf. Eq.(2). The synchrotron fit is essentially independent of mean strength $\langle B_\mathrm{d} \rangle$ of the internal field. The high-energy curves show the inverse Compton-SED in the CMB for the various field strengths. *(a)* for SN1006: The radio data are from [13] whereas the X-ray data are from RXTE [14], and Suzaku [15]. The Chandra data [16] are very similar to the Suzaku data and can be treated as indistinguishable in the present context. Also given are the upper limits from H.E.S.S.[5] and EGRET [17]. (b) for Tycho's SNR: The radio data are from [18], the X-ray data are from RXTE [14]. The γ-ray upper limit is from the HEGRA Cherenkov telescope (H-CT) system [6]. (c) for Kepler's SNR: The radio data are from [18], whereas the X-ray data are again from RXTE [14]. The γ-ray upper limits are from CANGAROO [7] and from H.E.S.S.[8].

that in such an approximately laminar gas flow the minimum strength of the internal magnetic field will always be lower than the strength of the upstream field and that the weighted average field strength is considerably lower than the maximum field strength (over the quasi-circular shock surface) immediately behind the shock, a more realistic estimate for the value of $\langle B_{\rm d} \rangle$ would be to put $\sigma \sim 1$. This would imply that the $\langle B_{\rm d} \rangle$ - values, given in Fig.1, roughly equal the values of B_0. This means that already the curves for $B_{\rm d} = 10\mu$G in the figures assume an unrealistically high ambient interstellar field strength, larger than the interstellar average. Yet they overpredict the IC γ-ray flux by at least one order of magnitude in comparison with the observed total γ-ray *upper limit* already for the very low-density object SN 1006 [19] – that would therefore be expected to be located in a lower than average interstellar magnetic field as well – and by much more for the two other sources.

Existing theoretical solutions for the overall particle acceleration in these three sources take into account the amplification of the magnetic field by the accelerating nuclear particles whose energy density becomes comparable to the kinetic energy of the incoming gas flow, as seen in the frame of the shock, e.g. [20], [21], [22]. Only then it seems possible to not overpredict the leptonic flux. At the same time the γ-ray flux is dominated by the hadronic flux, even though in SN 1006 only by a small margin.

IV. Conclusions

Simple one box approximations indicate that a leptonic scenario for the γ-ray emission from the three known Galactic type Ia SNRs SN 1006, Tycho's SNR and Kepler's SNR significantly overpredicts the γ-ray flux, even when compared to the existing upper limits from observations. The calculation makes direct use of the observed synchrotron emission spectra. Even though the arguments are simplistic, they appear to eliminate equally simplistic phenomenological arguments in favor of such a scenario. Any positive argument in favor of a purely leptonic scenario would therefore have to be based on a full solution of the governing nonlinear equations. From our results, however, we believe that such a positive argument can not be made.

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