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Inverse Compton gamma-ray models for remnants of Galactic type Ia supernovae? *(Research Note)*

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ABSTRACT

Aims. 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.

Methods. 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.

Results. 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 whose energy density substantially exceeds that of the synchrotron electrons, compatible with existing theoretical acceleration models for nuclear particles and electrons.

Conclusions. Even though the quantitative arguments are simplistic, they appear to eliminate simplistic phenomenological claims in favor of a inverse Compton γ-ray scenario for these sources.

Key words. ISM: cosmic rays – acceleration of particles – shock waves – radiation mechanisms: non-thermal – gamma rays: theory – supernovae: individual: SN 1006, Tycho's SN, Kepler's SN

1. 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. There are two ways to deal with this question in the investigation of an individual SNR.

The first approach is a theoretical one. It uses a nonlinear combination of gas dynamics (or eventually magnetohydrodynamics) for the thermal gas/plasma and kinetic transport theory for the collisionless, nonthermal relativistic particle component that is coupled with the plasma physics of the electromagnetic field fluctuations which scatter these particles. In the environment of the collisionless shock wave of a supernova explosion this allows the description of diffusive shock acceleration of the energetic particles which are originally extracted from the thermal gas and thus *injected* into the acceleration process. Since the field fluctuations are excited by the accelerating particles themselves and since the pressure of these particles (typically comparable with the thermal pressure) is reacting back on the thermal plasma, this strongly coupled system becomes a complex problem of nonlinear dynamics, not only for the charged particle components but also for the electromagnetic field and its fluctuations. Models suggest that a sizeable fraction of the entire hydrodynamic explosion energy will be transformed into energetic particle energy. This suggests that the SNRs are indeed the sources of the Galactic CRs.

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. Even assuming that the electron momentum distribution at high particle energies is only proportional to the total number of electrons injected per unit time at the shock, 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. This will be a key question in the discussion of this paper.

The injection of nuclear particles from the suprathermal tail of the momentum distribution produced in the dissipative shock transition is much better understood, because the same mechanism that produces scattering fluctuations for higher-energy nuclei – essentially a beam instability from the accelerated nuclei that is so strong that asymptotically the particles scatter along the mean field direction already after one gyro-period – also works at injection energies. In addition, where heavy ion injection takes place (Völk et al. 2003), it is to be expected that these ions dominate the nonthermal energy density behind a strong shock like in a young SNR. Then the main nonlinear shock modification consists in a weakening of the quasi-discontinuous part of the shock structure, associated with a broad shock precursor. Low energy particles – ions and electrons – in the accelerated spectrum are then only accelerated at this weaker subshock and this implies a significantly softer momentum spectrum at low energies than at high energies. This physical effect is visible in the radio part of the electron synchrotron spectrum and therefore a quantitative indication of the degree of shock modification. It provides a means to determine the injection rate of nuclear particles, de facto of protons, from the radio synchrotron spectrum. In all cases, where the synchrotron spectrum of SNRs was measured, this softening was observed. Together with the nonlinear theory of acceleration, and in the strong scattering limit, this determines the nonthermal pressure P_c, which turns out to be comparable with the kinetic pressure ρV_s^2 of the gas. Here V_s and ρ denote the shock velocity and the upstream mass density, respectively. Using therefore the synchrotron measurement, the nonthermal quantities can be determined from theory. The exception is at first sight the mean magnetic field strength. However, it needs to be consistent with the *overall form* of the synchrotron spectrum, from radio to X-rays, and with the X-ray synchrotron *morphology* that depends on the effective strength of the magnetic field. In this way an interior effective magnetic field strength is determined. It is typically an order of magnitude larger than the MHD-compressed upstream field strength. This amplification of the magnetic field is a characteristic of the effective acceleration of CR nuclei in a SNR, because it can only be the result of strong acceleration of nuclear particles. The pressure of the accelerated electrons – also for the cases discussed below – is more than two orders of magnitude below ρV_s^2.

The question is then, whether the observed γ-ray emission is also dominated by nuclear particles through their inelastic, π^0 – producing collisions with thermal gas nuclei. This need not be the case if the target density of the thermal gas is very low, despite the fact that the energy density of the accelerated nuclear particle component is very high, in fact comparable to the thermal energy density.

Using this theoretical approach (for reviews, see e.g. Malkov & Drury 2001; Völk 2004; Berezhko 2005, 2008) the investigation of half a dozen of *young* Galactic SNRs 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 (Berezhko & Völk 2007). Even though important details are open to debate because the time-dependent evolution of a point explosion can only be calculated numerically (Berezhko et al. 1996), we believe that this result is quite a robust one.

However, from a strictly observational point of view, the hadronic nature of most of the SNR γ-ray sources is not proven this way. This might ultimately be possible in a direct way with a very sensitive neutrino detector. The remaining question whether the Galactic CR population has a SNR origin then still requires the consistency of the observational result and the theoretical picture.

As far as γ-ray observations are concerned, there is also 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. For example, it can ask the question whether the necessarily limited dynamical range of the observed γ-ray emission allows a distinction between a hadronic and a leptonic scenario. Or it can ask whether observations in other wavelength ranges tend to empirically contradict the theoretically favored scenario of a predominantly nuclear energetic particle energy density. A possible topic consists in the interpretation of spatial correlations in resolved γ-ray SNRs, like those noted in RX J1713.7-3946 (Aharonian et al. 2006) and RX J0852.0-4622 (Vela Jr.) (Aharonian et al. 2007). The correlation of the hard X-ray synchrotron emission with the VHE γ-ray emission features might be considered to favor energetic electrons to produce both emissions. Discussions of the above and similar issues have recently been given for instance in Aharonian et al. (2006), Porter et al. (2006), Aharonian et al. (2007), Katz & Waxman (2008), Plaga (2008), and Berezhko & Völk (2008). However, the complexity of the configurations that characterize these extended sources introduces severe uncertainties. They arise from the poorly known structure of the circumstellar medium, which could be partly due to the strong winds expected from the progenitor stars or could be partly pre-existing in the form of neighboring interstellar clouds, affected by the progenitor and its subsequent explosion.

We shall add in this paper such a phenomenological argument. It concerns 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, HESS and CANGAROO experiments for SN 1006 (Aharonian et al. 2005), Tycho's SNR (Aharonian et al. 2001), and Kepler's SNR (Enomoto et al. 2008; Aharonian et al. 2008), 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.

2. 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 (e.g. Berezinskii et al. 1990)

$$E^2\frac{\mathrm{d}F^{\mathrm{syn}}}{\mathrm{d}E} = \frac{3\times 10^{-21}}{4\pi d^2}\int \mathrm{d}^3r\, B_\perp \times \int_0^\infty \mathrm{d}p\,p^2 f_e(\boldsymbol{r},p)\, g\left(\frac{E}{h\nu_c}\right) \quad (1)$$

in erg/(cm^2 s), where

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

$K_\mu(y)$ is the modified Bessel function, E is the photon energy, $\nu_c = 3eB_\perp p^2/[4\pi(m_e c)^3]$, 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 Crusius & Schlickeiser (1986) which is in turn closely approximated by substituting

$$B_\perp = \sqrt{2/3}B_d, \quad (2)$$

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

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 $f_\mathrm{e}(\boldsymbol{r}, p)$ equals the product of V and an electron distribution

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

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[1].

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:

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

in erg/(cm^2 s), where (Blumenthal & Gould 1970)

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

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 $\langle B_\mathrm{d}\rangle$.

3. 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 μG 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 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 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 $\langle B_\mathrm{d}\rangle$ would be to put $\sigma \sim 1$. This would imply that the $\langle B_\mathrm{d}\rangle$-values, given in Fig. 1, roughly equal the values of B_0. This means that already the curves for $B_\mathrm{d} = 10\ \mu$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 (Acero et al. 2007) – 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. Ksenofontov et al. 2005; Völk et al. 2005; Berezhko et al. 2006). 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.

[1] For internal magnetic field strengths in excess of 100 μG such a model distribution would have to include a high-energy part of the spectrum that is softened by synchrotron losses, see e.g. Berezhko et al. (2002). However in the present context, that does by assumption not include massive nuclear particle acceleration, such field strengths are not expected to occur.

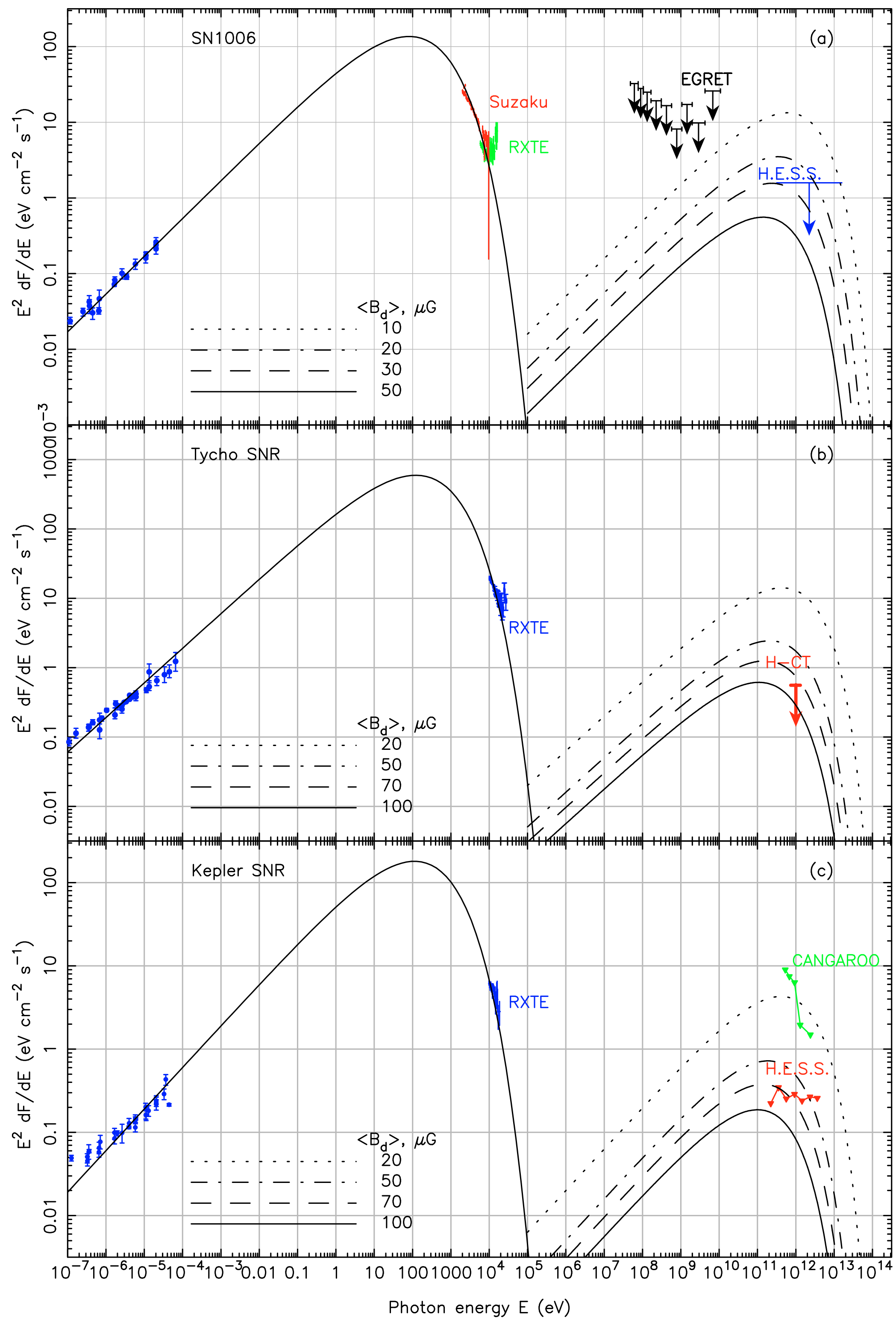

Fig. 1. The overall (spatially integrated) nonthermal spectral energy distribution (SED) as a function of photon energy E. The lower-energy part shows the simple fit to the observed synchrotron-SED, cf. Eq. (3), for various values of the internal field strength $B_{\perp}$ in μG, cf. Eq. (2). The synchrotron fit is essentially independent of the 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 *blue* radio data are from Reynolds (1996) whereas the *green* and *red* X-ray data are from RXTE (Allen et al. 1999), and Suzaku (Bamba et al. 2008), respectively. The Chandra data (Allen et al. 2004) are very similar to the Suzaku data and can be treated as indistinguishable in the present context. Also given are the upper limits from HESS (Aharonian et al. 2005) and EGRET (Naito et al. 1999). **b)** For Tycho's SNR: the radio data (in *blue*) are from Reynolds & Ellison (1992), whereas the X-ray data (in *blue*) are from RXTE (Allen et al. 1999). The γ-ray upper limit (in *red*) is from the HEGRA Cherenkov telescope (H-CT) system (Aharonian et al. 2001). **c)** For Kepler's SNR: the radio data (in *blue*) are from Reynolds & Ellison (1992), whereas the X-ray data (in *blue*) are again from RXTE (Allen et al. 1999). The γ-ray upper limits are from CANGAROO (Enomoto et al. 2008) (in *green*) and from HESS (Aharonian et al. 2008) (in *red*).

We note here that besides nonlinear amplification due to CRs the magnetic field in SNRs can also by amplified by other mechanisms. These are Rayleigh-Taylor instabilities at the contact discontinuity between the ejecta and the shocked circumstellar gas (e.g. Wang & Chevalier 2001) and the vorticity generation that results from the shock running into possibly pre-existing density inhomogeneities of the circumstellar medium (Giacalone & Jokipii 2007). However, the common feature of these mechanisms is that they act only in the downstream region and produce their main effect at a substantial distance behind the shock, that is outside the CR acceleration region. Therefore these mechanisms do not influence the CR acceleration process, in particular the maximal particle energy. Since accelerated CRs in young SNRs are concentrated in a thin layer near the shock front, these two mechanisms also hardly influence the properties of the nonthermal emission, produced by CRs, except possibly that of the highest-energy CRs.

4. 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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