EXPECTED GAMMA-RAY EMISSION OF SUPERNova REMnant SN 1987A

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ABSTRACT

A nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) is employed to re-examine the nonthermal properties of the remnant of SN 1987A for an extended evolutionary period of 5–100 yr. It is shown that an efficient production of nuclear CRs leads to a strong modification of the outer SNR shock and to a large downstream magnetic field $B_0 \approx 20$ mG. The shock modification and the strong field are required to yield the steep radio emission spectrum observed, as well as the considerable synchrotron cooling of high-energy electrons which diminishes their X-ray synchrotron flux. These features are also consistent with the existing X-ray observations. The expected $\gamma$-ray energy flux at TeV energies at the current epoch is nearly $\epsilon_\gamma F_\gamma \approx 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ under reasonable assumptions about the overall magnetic field topology and the turbulent perturbations of this field. The general nonthermal strength of the source is expected to increase roughly by a factor of two over the next 15–20 years; thereafter, it should decrease with time in a secular form.

Key words: acceleration of particles – gamma rays: general – ISM: individual objects (SN 1987A) – ISM: supernova remnants – X-rays: individual (SN 1987A)

1. INTRODUCTION

The supernova (SN) which occurred in 1987 in the nearby Large Magellanic Cloud was the first object of its kind in modern times whose evolution could be spatially resolved as a function of time; this includes the characterization of the progenitor star. SN 1987A has been extensively studied in all wavelengths from the radio to the $\gamma$-ray range. For a summary of its global characteristics, see, e.g., McCray (1993).

The properties and the future evolution of this SN can be viewed from different physics points of view. The present work concentrates on the nonthermal characteristics and, in particular, on the particle acceleration aspects and the expected $\gamma$-ray emission. It extends two earlier studies by Berezhko & Ksenofontov (2000), and by Berezhko & Ksenofontov (2006, hereafter referred to as BK), to include the subsequent Chandra observations of the soft and hard X-ray emission (Park et al. 2007), as well as the most recent and very detailed observations of the radio continuum emission by Zanardo et al. (2010). At the same time a qualitative and in fact semi-quantitative prediction of the future nonthermal emission from this source for the next decades is attempted.

The radio synchrotron emission and its spectral index are important for the determination of the nonthermal energy density in the source. In particular, the softness of the observed radio synchrotron spectrum shows that the radio electrons are accelerated in a rather weak shock. This is the plasma subshock formed when the accelerated nuclei modify the supernova remnant (SNR) blast wave by their pressure gradient, so that the main gas compression occurs in an extended cosmic ray (CR) precursor that does not accelerate radio electrons. This nonlinear modification determines the injection rate of the nuclear particles and vice versa (see BK and Section 3).

The new Chandra data in addition suggest that the hard X-ray emission is predominantly nonthermal. Since at the corresponding electron energies synchrotron losses are of overriding importance for the shaping of the X-ray synchrotron spectrum, these new observations also determine the effective magnetic field strength in the source (see Berezhko 2008, for a review). It turns out that these recent observations can be consistently explained with only minor modifications of the previous theoretical considerations. In particular, it can be shown that the circumstellar environment will lead to a further increase of the expected $\gamma$-ray emission in the next decades by a moderate factor of only about two, before the source will go into a steady emission decrease as the SNR shock leaves the immediate circumstellar environment and propagates secularly into the progenitor star’s unperturbed red supergiant (RSG) wind region.

In comparison with the other well-studied young, resolved SNR in the early sweep-up phase, which also exhibits nonthermal X-ray emission and a steep radio synchrotron spectrum, the Galactic object G1.9+0.3 that is presumably the remnant of a type Ia SN in an essentially uniform interstellar medium (ISM), SN 1987A, has a complex immediate circumstellar environment due to the interactions of its latest wind phases and the stellar radiation field before the explosion. This leads to a very nonuniform density structure interior to the stellar wind bubble formed by the progenitor in its RSG phase. Therefore, G1.9+0.3 and SN 1987A presumably constitute the extremes of spatially resolved pre-supernova circumstellar environments when studying the particle acceleration properties of extremely young SNRs. To this extent the present work is complementary to the analysis of the nonthermal properties of G1.9+0.3 (Ksenofontov et al. 2010). As one might expect on physics grounds, it turns out that in both cases the SN blast wave is already strongly modified by the accelerated particles—mainly atomic nuclei, called here CRs—from the very beginning of SNR formation, although the total amount of nonthermal energy, like that of thermal energy, is still only a percent fraction of the total explosion energy. This shock modification is associated with a strong amplification of the magnetic field strength in the swept-up circumstellar material. These conclusions are derived from the following observations: (1) the existence of nonthermal X-ray emission (see Section 4), (2) the rapid increase of the radio emission (see Murphy et al. 2008, for a recent analysis of the radio light curve for G1.9+0.3), and (3) the anomalously soft radio emission spectra (BK; Ksenofontov et al. 2010). In both cases the
evidence comes from the observed properties of synchrotron emission produced by the electron CR component. The electron component therefore plays a fundamental role, permitting indirect conclusions about key properties of the nuclear energetic particle component, such as its pressure and its amplification of the magnetic field. Given the diffuse radiation field, the inverse Compton gamma-ray emission by the electrons is then also determined and a measurement of the total gamma-ray emission yields the hadronic gamma-ray component.

SN 1987A and G1.9+0.3 are nevertheless distinct from other young historic Galactic SNRs such as the core-collapse object RX J1713.7+3946 and the type Ia object SN 1006, respectively, in that the latter SNRs have already swept up an amount of circumstellar matter that is approximately equal to the ejected mass. Therefore, they are expected by a number of authors to already contain an amount of nonthermal particle energy that corresponds to some 10% of the total hydrodynamic explosion energy (Aharonian et al. 2006; Berezhko et al. 2009; Berezhko & Volk 2010; Acero et al. 2010; Zirakashvili & Aharonian 2010; Ellison et al. 2010).

As a consequence of the softer effective equation of state of the combined gas–CR system, the dynamical evolution in this phase is different from that of a purely gas dynamic system. Also the increasing dissipation of hydromagnetic fluctuation fields will presumably influence the system (Ptuskin & Zirakashvili 2000, 2009), not to mention an early onset of radiative gas cooling as a result of the increased gas compression in the interior that is higher than the purely gas dynamic ratio of 4 (Dorfi 1991).

The observed shape of the remnant, especially at radio frequencies, is not very far from spherically symmetric, even though the observed emission varies around the remnant’s periphery (Potter et al. 2009). This suggests that a spherically symmetric model is a reasonable first-order approximation for a study of the general nonthermal properties of the remnant.

In the following section, an approximate spherically symmetric model of the pre-explosion environment of SN 1987A is formulated. This is combined in Section 3 with a theoretical, spherically symmetric, nonlinear model for the nonthermal evolution, using the earlier work of BK, and with the recent observations of the synchrotron emission, mentioned before. The results are presented in Section 4 and summarized in Section 5.

2. APPROXIMATE SPHERICALLY SYMMETRIC MODEL OF THE CIRCUMSTEELLAR ENVIRONMENT SNR 1987A

The initial short outburst of radio emission (Turtle et al. 1987) has been attributed to the synchrotron emission of electrons accelerated by the SN shock propagating in the free wind of the blue supergiant (BSG) progenitor star (Chevalier & Fransson 1987). After about three years radio emission was detected again (Staveley-Smith et al. 1992; Gaensler et al. 1997), as well as a monotonically increasing X-ray emission (Gorenstein et al. 1994; Hasinger et al. 1996). This second increase of emission has then been attributed to the entrance of the outer SN shock into the wind bubble of the BSG of density $\rho_n$, thermalized in a termination shock at a radial distance $R_T = 3.1 \times 10^{17}$ cm (e.g., Berezhko & Ksenofontov 2000), and subsequently into an H II region of much denser matter, consisting of the swept-up wind of an RSG precursor phase (Chevalier & Dwarkadas 1995). The density $\rho_R$ of the swept-up RSG wind region is large compared to $\rho_n$. The contact discontinuity between the two winds is assumed at $R_C = 5 \times 10^{17}$ cm and the scale $l_C$ of a modeled smooth transition is assumed as $l_C = 0.05 R_C$.

These parameters are consistent with canonical values of stellar ejecta mass $M_{ej} = 10 M_\odot$, distance $d = 50$ kpc, and hydrodynamic explosion energy $E_{sn} = 1.5 \times 10^{51}$ erg (e.g., McCray 1993). During an initial period the ejecta material has a broad distribution in velocity $v$. The fastest part of this distribution can be described by a power law $dM_{ej}/dv \propto v^{2-k}$. The present modeling uses a value $k = 8.6$ appropriate for SN 1987A (McCray 1993). The general picture is that the interaction of the ejecta with the circumstellar medium (CSM) creates a strong shock there which heats the thermal gas and accelerates particles diffusively to a nonthermal CR component of comparable energy density.

According to Chevalier & Dwarkadas (1995), the CSM at $r > R_C$ includes three subsequent regions: the H II region, an equatorial ring, and, beyond the ring, a free RSG wind (followed further out by a rarefied main-sequence wind bubble which is of no concern here). The contact discontinuity between the two winds is in reality not a spherical surface at radius $R_C$, nor is the equatorial ring a spherical shell, as the optical observations clearly indicate (McCray 1993; Chevalier & Dwarkadas 1995).

Nevertheless, the present nonthermal model approximates the mass distribution $\rho_{ER}$ within the ring by a spherically symmetric shell

$$\rho_{ER} = \rho_n \exp[-(r - R_R)^2/l_R^2],$$

(1)

where $\rho_n \approx M_{sh}/(4\pi R_C^3)$ is the central (maximal) density of the shell and $M_{sh}$, $R_R$, and $l_R$ represent the total mass, radius, and width of the shell, respectively. Below, the values $R_R = 7 \times 10^{17}$ cm and $l_R = 0.25 R_R$ are used. $l_R$ approximately corresponds to the interval of radial distances where the dense cool shell, associated with the equatorial ring, is positioned around the source (Crots et al. 1995).

In the same spirit, the density profile of the RSG matter consists of three corresponding terms:

$$\rho_R = \rho_{H}(R_R - r) + \rho_{ER} + \rho_{w} H(r - R_R).$$

(2)

Here, $H(x)$ is the Heaviside function.

This results in the following model for the CSM density distribution at the distances $r > R_T$ in the form

$$\rho V_0 = \frac{\rho_n + \rho_R}{2} - \frac{\rho_n - \rho_R}{2} \tan \frac{r - R_C}{l_C}. \tag{3}$$

For the gas number density $N_g = \rho/m_p$, the following values are adopted: $N_g^{II} = 0.29$ cm$^{-3}$, $N_g^{III} = 280$ cm$^{-3}$, where $m_p$ is the mass of proton. These values, as shown by BK, provide a good compromise between the SN shock dynamics seen in the radio and X-ray emissions.

Since the density of the free RSG wind can be expressed in the form

$$\rho_w = \frac{M}{4\pi V_w r^2}, \tag{4}$$

where $M$ is the RSG mass-loss rate and $V_w$ denotes the RSG wind speed, the mass of the shell can be expressed in the form

$$M_{sh} = \frac{MR_R}{V_w} - \frac{4\pi \rho_n (R_R^3 - R_C^3)}{3}. \tag{5}$$

It is assumed that the center of the spherically smoothed ring is positioned exactly at the boundary $r = R_R$ between the H II region and the free RSG wind region.

According to Blondin & Lundqvist (1993), the RSG mass-loss rate $M$ is highly nonuniform: it is $M = 8 \times 10^{-5} M_\odot$ yr$^{-1}$.
in the equatorial region within $\pm 9^\circ$ and $M = 4 \times 10^{-6} M_\odot \text{yr}^{-1}$ in all other directions. In the present spherically symmetric approximation, its average value is then $M = 1.6 \times 10^{-3} M_\odot \text{yr}^{-1}$.

For the conventional value $V_s = 5 \text{ km s}^{-1}$ of the RSN speed, the mass of the shell is $M_{sh} = 0.5 \times M_\odot$.

3. PARTICLE ACCELERATION MODEL

To describe the observed properties of nonthermal emission of SN 1987A a nonlinear kinetic theory is used here. It couples the particle acceleration process with the hydrodynamics of the thermal gas (Berezhko et al. 1996; Berezhko & Völk 2000). Therefore, in a spherically symmetric approach it is able to predict the evolution of gas density, pressure, mass velocity, together with the energy spectrum and the spatial distribution of CR nuclei and electrons at any given evolutionary epoch $t$, and the properties of the nonthermal radiation produced in SNRs due to these accelerated particles.

The model does not contain the reverse shock propagating in the SN ejecta. The reverse shock is not expected to be an efficient CR accelerator, because the magnetic field value is expected to be very weak as a result of the large expansion of the exploded stellar material that leads to inefficient high-energy CR acceleration. Even if one assumes equally efficient CR injection/acceleration on the forward and the reverse shock, the expected energy content of CRs accelerated by the forward shock is considerably larger compared with the reverse shock except during the transition phase from the free expansion to the Sedov SNR phase (see Berezhko & Ksenofontov 2000, for more details). Since SN 1987A is still far from the Sedov phase, one can neglect the contribution of the reverse shock to the nonthermal emission of the remnant. In addition, the analysis of the observed fine structure of the X-ray and radio emission (Zhekov et al. 2010) gives evidence that they are produced by the forward shock (blast wave).

In the particle acceleration model, the scattering properties of the CSM are required. Given the enormous shock velocities in excess of $\approx 5000 \text{ km s}^{-1}$ (see the following section), Bohm diffusion appears a most reasonable approximation. It was also used by BK. In this limiting case the scattering mean free path equals the particle gyroradius and is therefore inversely proportional to the mean magnetic field strength $B$.

A rather high downstream magnetic field strength $B_d \approx 10 \text{ mG}$ is required to reproduce the observed radio and X-ray spectra (BK). It is far from obvious that the dynamical interaction of the RSG and BSG wind systems, responsible for the inferred circumstellar structure, can also lead to such high magnetic field strengths. It is much more likely that the required strength of the magnetic field has to be attributed to nonlinear field amplification at the SN shock by the CR acceleration process itself. According to plasma physical considerations going back to Lucek & Bell (2000) and Bell (2004), the existing CSM magnetic field can indeed be significantly amplified at a strong shock by CR streaming instabilities. In fact, for all the thoroughly studied young SNRs, the ratio of magnetic field energy density $B_0^2/8\pi$ in the upper region of the shock precursor to the CR pressure $P_c$ is about the same (Völk et al. 2005). Here, $B_0$ is the far upstream field in the precursor, presumably amplified by the energetically dominant CRs of the highest energy. Within an error of about 50% the empirical relation

$$B_0 = \sqrt{2\pi \times 10^{-2} \rho V_s^2}$$

holds, where $V_s$ denotes the SN shock speed. This is quantita-

![Figure 1. Shock radius $R_s$ (solid), shock speed $V_s$ (solid), gas density $N_g$ (dashed-dotted), and upstream magnetic field $B_0$ (dashed) at the current shock position as a function of time since SN explosion for $R_{sh} = 7 \times 10^{17} \text{ cm}$. The dotted vertical line marks the current epoch. The observed radius and speed of the SN shock, as determined by radio observations (Ng et al. 2008), are shown as well. The scaling values are $R_i = R_s = 3.1 \times 10^{17} \text{ cm}$ and $V_i = 28,000 \text{ km s}^{-1}$.

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As reviewed earlier (Völk 2004; Berezhko 2005, 2008), and elaborated most recently in detail (Berezhko et al. 2009; Ksenofontov et al. 2010), the key parameters of the theoretical model (proton injection rate $\eta$ and electron-to-proton ratio $K_{ep}$ below the synchrotron cooling range) can be determined in a semi-empirical way from a fit of the nonlinear theoretical solution to the observed synchrotron emission spectrum. For the sake of simplicity, the values of these parameters are usually assumed to be constant during SNR evolution. Also BK proceeded in this way. The present paper assumes such a simplification to be the main reason why a corresponding theoretical model fits the data only on average. This concerns the shape of the radio spectrum and the time dependence of the radio flux over an extended period of SNR evolution (Zanardo et al. 2010). In the case of SN 1987A, on the other hand, it is natural to expect substantial time variations of these injection parameters since the SN shock propagates through a strongly nonuniform CSM whose physical parameters at the shock front are expected to change in time. Therefore, in contrast to BK, time-dependent injection parameters $\eta(t)$ and $K_{ep}(t)$ will be admitted here. Their values are determined from the fit to the measured synchrotron data. The main physical factor that determines the injection efficiency $\eta(t)$ is the structure of the magnetic field upstream of the shock. Injection is expected to be progressively less efficient when the magnetic field component tangential to the shock surface becomes more relevant (Völk et al. 2003). Such a situation is expected in the

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most compressed CSM region, that is, in the ring region. It is important to note that a reliable semi-empirical estimate for the values of these parameters for any given SNR evolutionary phase is possible if the measured synchrotron spectra in the radio and X-ray bands are available for this particular phase (e.g., Berezhko et al. 2009; Ksenofontov et al. 2010). For SN 1987A good quality measurements of the radio spectrum, as well as of the X-ray fluxes in the soft (0.5–2 keV) and hard (3–10 keV) energy ranges, exist now for the full evolutionary period (e.g., Zanardo et al. 2010). The remaining problem is that the nature of the observed X-ray emission of SN 1987A is not known unequivocally. In the extreme case, when only an upper limit for the nonthermal (synchrotron) emission is known, the data yield only a lower limit for the magnetic field strength $B_0(t)$ and a corresponding value of the electron-to-proton ratio (BK). It is, however, noted here that the time dependence of the hard X-ray flux differs from that of the soft X-ray flux, and that it is very close to the time dependence of the radio emission flux. This fact can be interpreted as evidence that the hard X-ray emission is predominantly of a nonthermal nature (e.g., Zanardo et al. 2010). The considerations below are based on this interpretation.

The present model calculations start at the SNR evolutionary epoch $t = 1000$ days, when the outer SN shock has reached a radius $R_1 = R_T$ and a speed $V_1 = 28,000$ km s$^{-1}$. These values of $R_1$ and $V_1$ correspond to the end of the SN shock propagation in the free BSG wind region $r < R_T$ (BK). The contribution of CRs accelerated in the region $r < R_T$ is neglected, because the number of CRs produced in the region $r > R_T$ becomes dominant very soon, because of the high gas density there.

4. RESULTS AND DISCUSSION

The calculated shock radius $R_s$ and shock speed $V_s$, shown in Figure 1 as a function of time, are in satisfactory agreement with the values obtained on the basis of radio measurements. Up to the year 2030 the shock speed decreases due to the increase of the CSM density and then, after crossing the maximal CSM density, it increases again from $V_s = 3300$ km s$^{-1}$ to $V_s = 4400$ km s$^{-1}$. The reason for this unexpected behavior is that during the entire time period under consideration the swept-up mass is much lower than the ejecta mass $M_{ej}$. Therefore, the main fraction of the explosion energy is contained in the freely expanding ejecta. On a small timescale the shock is driven by the downstream overpressure: each local relatively sharp increase of the CSM density leads to a temporal decrease of the shock speed that keeps $\rho_0 V_s^2$ constant. However, on a larger timescale the shock is piston driven.

Note that the actual CSM is essentially non-spherically symmetric during the time period considered. Despite of this situation the piston-driven shock is expected to be roughly spherical. This supports the spherically symmetric approach used here.

The fit of the theoretical solution to the synchrotron spectra, as measured in the radio and X-ray ranges up to the year 2008 (Zanardo et al. 2010), yields estimates for the proton injection rate $\eta(t)$ and for the electron-to-proton ratio $K_{ep}(t)$. This is shown in Figure 2. The fit procedure was described in detail for similar cases (Berezhko et al. 2009; Ksenofontov et al. 2010). The required proton injection rate $\eta(t) \approx 10^{-3}$ leads to a significant nonlinear modification of the shock: as can be seen in Figure 2 the total shock compression ratio $\sigma = 5.4–6$ is essentially larger and the subshock compression ratio $\sigma_s \approx 2.8–3.6$ is lower than the classical value of 4 for a pure gas shock. Figure 2 also shows that the proton injection rate $\eta$ changes during the SNR evolution, so that it has a local minimum at an age of about 20 years. This is required in order to fit the observed radio emission spectra, which are becoming somewhat harder than a spectrum calculated with an unchanged injection rate—at least up to the present time. During the period from $t \approx 13$ yr to $t \approx 30$ yr, i.e., beyond the present epoch of radio observations, the shock is within the dense shell that corresponds to the observed equatorial ring. In this spatial region the magnetic field is expected to have an enhanced tangential component which should depress the nuclear injection rate.

Thereafter, the injection rate is a priori unknown. It may increase again to the same level $\eta(t) \approx 10^{-3}$. This is one of the possibilities calculated below (so-called high proton injection rate). However, since the magnetic field vector in the free RSG wind is dominated by a component tangential to the SNR shock, the possibility of a continuing depressed injection (so-called low proton injection rate) at a level similar to the value $\eta(t) \approx 4 \times 10^{-4}$ within the ring region is also considered.

The higher injection rate yields for $t > 23$ yr a correspondingly larger shock modification, characterized by a larger shock compression ratio $\sigma$ and a lower subshock compression ratio $\sigma_s$ (Figure 2).

The strongly modified SNR shock generates a CR spectrum $N \propto p^{-\gamma}$, which is very soft at momenta $p < m_p c$, with index $\gamma \approx (\sigma_s + 2)/(\sigma_s - 1) \approx 2.7$. CR electrons with such a spectrum produce a radio synchrotron emission spectrum $S_\nu \propto \nu^{-\alpha}$ with spectral index $\alpha = (\gamma - 1)/2 \approx 0.9$, that corresponds very well to the observations, as can be seen in Figure 3, where the synchrotron spectral energy density $\nu S_\nu$ is calculated for five successive epochs together with the experimental data.

The assumed time variation of the proton injection rate $\eta(t)$ leads to a time dependence of the radio spectral index $\alpha$ as shown in Figure 4, and it provides a better fit of the observations (Zanardo et al. 2010) compared with the case of constant $\eta$ (BK). In fact, the adopted injection rate $\eta(t)$ at $t < 20$ yr is the result of the fit to the radio synchrotron spectrum.

For the future, $t > 20$ yr, the slope of the radio synchrotron spectrum is expected to be nearly the same if the proton injection
remains constant at $\eta \approx 4 \times 10^{-4}$ (Figure 4). It is expected to become progressively steeper due to the decrease of the subshock compression ratio $\sigma_s(t)$ in case the proton injection rate increases again to the level $\eta \approx 10^{-3}$.

The strong downstream magnetic field $B_d \approx 20$ mG leads to synchrotron cooling of the electrons with momenta $p > 10 m_e c$. This makes the high-energy part of the synchrotron spectrum ($\nu > 10^{13}$ Hz) very soft (see Figure 3). At higher frequencies ($\nu = 10^{16} - 10^{19}$ Hz) the synchrotron spectrum becomes harder, possibly due to a pile-up effect. It hardens the spectrum of accelerated electrons, that undergo strong synchrotron losses, just near its exponential cutoff (e.g., Drury et al. 1999). Under this condition the calculated synchrotron flux at frequency $\nu \approx 10^{17}$ Hz, which corresponds to a photon energy $\epsilon_\gamma = 0.5$ keV, is below the measured flux (see Figure 3). This is a required condition because at energies $\epsilon_\gamma = 0.5 - 2$ keV, the X-ray emission of SN 1987A is dominated by lines and is therefore mainly of thermal origin. At higher energies $\epsilon_\gamma > 3$ keV X-rays are presumably of a predominant nonthermal origin. Therefore, the fit of the measured X-ray flux for $\epsilon_\gamma = 3$ keV was used in the determination of the values of the injection parameters ($\eta(t)$ and $K_{ep}(t)$) and of the amplified magnetic field $B_0(t)$ at the beginning of the shock precursor.

The less modified shock corresponding to a low injection rate during the future epoch $t > 23$ yr yields lower cooling of electrons due to the lower downstream magnetic field on account of the lower overall compression ratio. This leads to a considerably flatter high-energy part of the synchrotron spectrum ($\nu > 10^{13}$ Hz).

The calculated $\gamma$-ray integral spectral energy flux density (SED), shown in Figure 5, is dominated by the $\pi^0$-decay component at all energies.

It is important to note here that the hadronic SED has nevertheless been renormalized by a factor $f_{\text{rec}} = 0.2$ compared with the amplitude resulting from the spherically symmetric model on which the entire calculation is predicated (e.g., Völk et al. 2003). The reason for this a posteriori correction is the fact that the circumstellar environment is characterized by an Archimedean spiral topology, both in the BSG as well as in the RSG wind bubble environment. In particular, the radiative cooling and the ionization by the stellar radiation field of the progenitor star will make the entire interaction region of these successive wind phases highly turbulent. Therefore, there will always be regions where the SNR is quasi-parallel, that is to say, regions where the shock normal will make an relatively small angle with the local upstream magnetic field direction. Only in these quasi-parallel shock regions nuclear particles can be effectively injected into the diffusive acceleration process. However, as a consequence of the overall Archimedean spiral topology, the total solid angle of these quasi-parallel shock segments will be $4\pi f_{\text{rec}}$, where $f_{\text{rec}}$ is considerably smaller than unity. Following previous estimates (Völk et al. 2003; Berezhko et al. 2003) $f_{\text{rec}} = 0.2$ is used in this paper, but the actual value of $f_{\text{rec}}$ may be even smaller. The corresponding uncertainty in the amplitude of the $\gamma$-ray energy flux remains.

Since the SN shock is strongly modified, the $\gamma$-ray spectrum at energies $\epsilon_\gamma > 0.1$ TeV is very hard: $F_\gamma \propto \epsilon_{\gamma}^{-0.8}$. At the current epoch the expected $\gamma$-ray energy flux at TeV energies is about $\epsilon_\gamma F_\gamma \approx 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, and during the next 20 years it is expected to grow by a factor of about two with a subsequent temporal decrease $F_\gamma \propto R_s^{-1}$ due to the rapid spatial decrease of the CSM density $\rho_w(R_s) \propto R_s^{-2}$ (e.g., Berezhko & Völk 2000).
At present there exist only upper limits for the TeV emission. They have been obtained by the CANGAROO (Enomoto et al. 2007) and H.E.S.S. (Komin et al. 2010) instruments (see Figure 5). The latest H.E.S.S. upper limit is quite close to the SED estimated above. Even with the reservations formulated above, this is remarkable and justifies in the view of the present authors a deep observation of this object.

The expected time profile $F_\gamma(t)$ is sensitive to the radial profile of the actual CSM density distribution. If the dense shell, which in the spherically symmetric model represents the matter contained in the equatorial ring, is situated at a larger distance, say at $R_R = 9 \times 10^{17}$, the peak of $\gamma$-ray flux is expected to occur 10 years later, with an amplitude that is by a factor of 1.3 lower than in the former case.

It is clear from the above consideration that the proton injection rate $\eta$ (whose value influences the efficiency of CR production) can be estimated from the observed shape of the radio emission. Since it is not possible to predict the values of $\eta$ for the future evolutionary epochs, the presented prediction for the corresponding gamma-ray emission is uncertain. Note however that this kind of uncertainty is not very big due to the following reasons. First of all, it is hard to expect that the shape of the radio spectrum will be much more rapidly changing during the next 20–30 years than during the previous epochs. Therefore, the predictions based on the recently determined value of $\eta$ should be roughly valid also for this period of time. Second, the shape of the CR spectrum is strongly sensitive to the injection rate at low energies $\epsilon < m_p c^2$. Since the radio synchrotron emission is produced by electrons with such energies, it is sensitive to the expected injection rate (Figures 3 and 4). The high-energy part of the CR spectrum ($\epsilon > m_p c^2$) is less sensitive to $\eta$: variations of $\eta$ by a factor of three at the epoch $t > 40$ yr (see Figure 2) only lead to a variation of the CR pressure $P_\gamma / (\rho_0 V_\infty^2) \approx 1 - \alpha_\gamma / \sigma$ by a factor of 1.5. Since the CR pressure is dominated by the highest energy CRs, one should expect a corresponding variation of the high-energy gamma-ray emission. This is indeed seen from Figure 5: for $t > 40$ yr the expected gamma-ray flux at energies $\epsilon_\gamma = 1$–10 TeV for a low injection rate is lower by a factor $\sim 1.5$ compared with the case of high injection.

Therefore, taking into account the uncertainties of all relevant parameter values, we expect that the prediction for the TeV emission is uncertain at best by a factor of two (Figure 5).

5. SUMMARY

A kinetic nonlinear model for CR acceleration in SNRs has been applied in detail to SN 1987A, in order to compare its results with observed properties. It is found that quite reasonable consistency with most of the observational data can be achieved.

The evidence for efficient CR production, leading to a strong shock modification of the shock, comes from the radio synchrotron data. A proton injection rate of $\eta \approx 10^{-3}$ is required to produce a significant shock modification that leads to the steep spectrum of energetic electrons which fits the observed synchrotron spectrum very well. The condition is an extremely high downstream magnetic field strength $B_0 \sim 10$ mG. Such a high field implies significant synchrotron losses of CR electrons emitting nonthermal X-rays. This makes the high-frequency part of the synchrotron spectrum much softer and is consistent with the high-energy part of the X-ray spectrum, which is presumably of nonthermal origin. Therefore, the fit of the synchrotron spectrum gives a good estimate for the CR injection parameters and makes it possible to calculate the expected $\gamma$-ray flux in a spherically symmetric model. However, the basic tendency of the magnetic field vectors to form an Archimedean spiral configuration in the circumstellar wind interaction region requires a renormalization of the overall $\gamma$-ray flux. This a posteriori reduction by a factor $f_\gamma = 0.2$ is chosen following the previous analyses of other SNRs. This introduces an acknowledged uncertainty in the predicted overall $\gamma$-ray flux.

Since the SN shock interacts with the cool shell which is the densest part of the CSM, the $\pi^0$-decay $\gamma$-ray SED at the current epoch is already quite high $\epsilon_\gamma F_\gamma \approx 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ at energies $\epsilon_\gamma = 0.1$–10 TeV. Depending upon the details of the CSM distribution during the next 15–20 years, the $\gamma$-ray flux is expected to increase roughly by a factor of two.

The further temporal evolution of the gamma-ray emission corresponds to a secular decrease because the gas density in the unperturbed RSG wind region decreases with radius $\propto r^{-2}$. Since the particle injection into the shock acceleration process cannot be well determined for this later phase, the precise form of the emission decrease is not well known.

The detection of $\gamma$-ray emission from SN 1987A would be a very important element in a consistent picture for this SNR. In particular, it would give evidence for efficient CR production followed by strong magnetic field amplification for a core-collapse SN at a very early stage of its remnant.

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