Gamma-ray Emission Expected from Young Supernova Remnants

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Abstract

We briefly analyse the results of the nonlinear kinetic model of cosmic ray (CR) acceleration in supernova remnants (SNRs) applied to young SNRs (Tycho's, SN 1006 and Cassiopeia A SNRs) in order to describe their relevant properties. It is shown that the theory fits the existing data in a satisfactory way within set of parameters consistent with the idea that all these SNRs are typical sources of Galactic CRs. A rather high interior magnetic field 0.1 to 1 mG is required to give a good fit for the radio and X-ray synchrotron radiation. In all cases π^0-decay γ-rays generated by the nuclear CR component dominates over γ-rays, generated by electron CR component, and calculated γ-ray flux fits existed data.

1. Introduction

The main reason why one might expect supernova remnants (SNRs) to be a cosmic ray (CR) source is a simple argument about the energy required to sustain the Galactic cosmic ray (GCR) population against loss by escape, nuclear interactions and ionization energy loss. The mechanical energy input to the Galaxy from each supernova (SN) is about 10^{51} erg so that with a rate of about one every 30 years the total mechanical power input from supernovae is of the order 10^{42} erg/s [1]. Thus supernovae have enough power to drive the GCR acceleration if there exists a mechanism for channeling about 10% of the mechanical energy into relativistic particles. The high velocity ejecta produced in the supernova explosion interacts with the ambient medium to produce a system of strong shocks. The shocks in turn can pick up a few particles from the plasma flowing into the shock fronts and accelerate them to high energies.

The only theory of particle acceleration which at present is sufficiently well developed and specific to allow quantitative model calculations, and which appears capable of meeting many of the observational constraints on any CR acceleration theory, is diffusive acceleration applied to the strong shocks associated with SNRs.

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Considerable efforts have been made during the last years to empirically confirm the theoretical expectation that the main part of GCRs indeed originates in SNRs. Theoretically progress in the solution of this problem has been due to the development of the kinetic nonlinear theory of diffusive shock acceleration [2-4]. Although still incomplete, the theory includes all the most relevant physical factors, essential for SNR evolution and CR acceleration, and it is able to explain the main characteristics of the observed GCR spectrum under several reasonable assumptions, at least up to an energy of $\sim 10^{15}$ eV [5].

Direct information about high-energy CR population in SNRs can be obtained from the observations of the emission produced by accelerated CRs in SNRs. Electron CR component is very well visible in a wide wave length range of radiation, which they produce in SNRs, from radio to γ-ray emission, whereas in the case of nuclear CR component the γ-ray detection is the only possibility to fiend it. If this nuclear component is strongly enhanced inside SNRs then through inelastic nuclear collisions, leading to pion production and subsequent decay, γ-rays will be produced at the detectable level [6,3,4].

High-energy γ-rays can also be produced by CR electrons due to the inverse Compton (IC) scattering of the background photons. Therefore it is not so obvious which CR component (nuclear or electron) produces TeV emission, detected from SN 1006 and Cas A. For this interpretation SNR magnetic field value plays the crucial role. It is argued that it is considerably larger compared with the typical interstellar magnetic field. High field is required to produce in SNRs CR power-law spectrum at least up to the knee energy 3×10^{15} eV [5]. There are some evidences extracted from the synchrotron radiation data that the actual magnetic field in young SNRs is indeed essentially enhanced.

We briefly analyse the situation in young SNRs (SN 1006, Tycho's and Cassiopeia A (Cas A) SNRs) on the basis of nonlinear kinetic diffusive shock acceleration model and conclude that all the observed characteristics of these young SNRs are consistent with the idea that SNRs are the main source of GCRs.

2. Essential SNR parameters

There are a number of physical parameters, which values are needed to be known to describe the observed properties of young SNRs. SN explosion energy $E_{\rm sn}$, ejecta mass $M_{\rm ej}$, interstellar medium (ISM) number density $N_{\rm H}$ directly determine the SNR dynamics, the observed size and speed of SN shock.

At the same time there are two other physical parameters which essentially influence the efficiency of the diffusive shock acceleration and its final significance.

The first one is the injection rate, which is the number of the gas particles swept up by the shock and involved into the acceleration. The number of suprathermal protons injected into the acceleration process is described by a dimensionless injection parameter η which is a fixed fraction of the ISM particles entering the shock front. Unfortunately there is no complete selfconsistent theory of a collisionless shock transition which can predict the value of the injection rate and its dependence on the shock parameters. For the case of a purely parallel plane shock hybrid simulations predict a quite high ion injection (e.g. [7,8]) which corresponds to the value $\eta \sim 10^{-2}$. Such a high injection is consistent with analytical models [9,10] and confirmed by measurements near the Earth's bow shock [11]. We note however that in our spherically symmetric model these results can only be used with some important modification [12]. Assuming nucleon injection to occur through the leakage of suprathermal particles into the upstream region from behind the shock, the relevant injection velocity parallel to the magnetic field increases when the shock becomes more and more oblique. Therefore the injection is expected to be strongly suppressed at the quasi-perpendicular surface fraction of the shock and this surface fraction is larger than that of the quasi-parallel fraction due to the field refraction. This lack of symmetry in the actual SNR can be approximately taken into account by a renormalization factor $f_{\rm re} < 1/2$ which diminishes the nucleonic CR production efficiency as calculated in the spherical model, and all effects associated with it. An estimate yields roughly $f_{\rm re} = 0.15$ to 0.25 [12].

Depending upon the external magnetic field structure one can expect few sports on the shock surface with the efficient CR injection/acceleration, as in the case of SN 1006 where due to presumably almost uniform external magnetic field efficient acceleration takes place in two polar regions, or many such spots if external field is strongly disordered on the SN shock size. The latter situation presumably takes place in Cassiopeia A (Cas A) SNR.

Note that usually predicted by the model, the CR acceleration efficiency is significantly higher than required for the average replenishment of the Galactic CRs by SNRs, corresponding to $E_{\rm c} \approx 0.1 E_{\rm sn}$. This discrepancy can be attributed to the physical conditions at the shock surface (magnetic field geometry) which influence the injection efficiency and the number of nuclear CRs, calculated within the spherically-symmetrical approximation, should be renormalized by the depression factor $f_{\rm re}$.

If one takes into account the Alfvén wave excitation due to CR streaming (which becomes efficient already at a very low injection rate $\eta \sim 10^{-7}$) the local injection rate has to be averaged over the fluctuating magnetic field directions and is much lower than for the purely parallel case. It is why the appropriate values of the injection rate η, which fits the data, lies within the range from 10^{-4}

to 10^{-3}.

Magnetic field strength, the second important parameter, plays a twofold role. First of all, it determines the upper energy of CRs which could be achieved during the SNR evolution

$$\epsilon_{max} \propto B. \tag{1}$$

To produce in SNRs CR power-law spectrum at least up to the knee energy 3×10^{15} eV, which we believe is a necessary condition for GCR source, one need magnetic field several times larger than the typical ISM field [5]. Such a large field can be either preexisted field in the circumstellar medium or it can be an amplified interstellar field due to the CR backreaction effect. According to the numerical simulation [13], the existing ISM magnetic field can indeed be significantly amplified near a strong shock by CR streaming.

Radio observations of synchrotron emission is powerful probes of magnetic fields and electron distributions in SNRs. Electrons with a power-law energy spectrum

$$N_e(\epsilon) \propto N_0 \epsilon^{-\gamma} \tag{2}$$

produce the synchrotron flux

$$S_\nu \propto N_0 B^{(\gamma+1)/2} \nu^{-\alpha} \tag{3}$$

with the spectral index $\alpha = (\gamma - 1)/2$. In the test-particle limit power-law index $\gamma = 2$ and therefore $\alpha = 0.5$. Values $\alpha > 0.5$ observed in young SNRs require curved electron spectrum (hardening to higher energies) as predicted by nonlinear shock acceleration models.

The synchrotron emission at frequency ν are mainly produced by electrons of energy

$$\epsilon = 5\sqrt{\left(\frac{\nu}{1\ \mathrm{GHz}}\right)\left(\frac{10\ \mu\mathrm{G}}{B}\right)} \quad \mathrm{GeV}. \tag{4}$$

Since typical particle spectrum produced by modified shock [2-5] is characterized by $\gamma > 2$ at $\epsilon < 1$ GeV and $\gamma < 2$ at $\epsilon > 10$ GeV it follows from the above relation that to have $\alpha > 0.5$ one needs not only efficient CR acceleration with the subsequent shock modification but also high magnetic field $B >> 10\ \mu$G in the acceleration region.

Since for given synchrotron flux S_ν required number of electrons $N_0 \propto S_\nu / B^{(\gamma+1)/2}$, the relative role of electrons in high-energy γ-ray production is lower for higher SNR magnetic field value B.

It is important to note that in the case of strong magnetic field in SNR the electron spectrum is bounded at lower maximum energy ϵ_{max} than protons due to synchrotron losses. It gives the natural explanation to the fact that the value of ϵ_{max} extracted from the X-ray observation is so small $\epsilon_{max} \sim 10$ TeV, that these SNRs can hardly be considered as a source of GCRs, if proton spectrum is bounded by the same upper energy as expected at low magnetic field.

3. Supernova remnant SN 1006

The nonlinear kinetic model for CR acceleration in SNRs has been applied to SN 1006 in order to explain its observed properties [14]. We have used stellar ejecta mass $M_{\rm ej} = 1.4 M_{\odot}$, distance $d = 1.8$ kpc, and ISM number density $N_{\rm H} = 0.3$ cm^{-3} from X-ray and optical imaginary of SN 1006. For these parameters an explosion energy $E_{\rm sn} = 3 \times 10^{51}$ erg is required to fit the observed size $R_{\rm s}$ and expansion speed $V_{\rm s}$ which are determined by the ratio $E_{\rm sn}/N_{\rm H}$.

It was demonstrated that for low magnetic field all the observed emissions can be dominated by the electron contribution. Protons are then assumed to be injected into the acceleration much less efficiently than electrons and do not produce any essential shock modification. For this so-called inefficient model ($\eta = 10^{-5}$) the lowest permitted value of the electron to proton ratio is $K_{\rm ep} = 0.04$. It exceeds the canonical value 0.01 observed in situ in the neighborhood of the Solar System for the Galactic CRs. The maximum energy of accelerated CRs and their total energy content in this case are only $\epsilon_{\rm max} \sim 10^{13}$ eV and $E_{\rm c} < 3 \times 10^{49}$ erg respectively. These numbers are too low for such SNRs to be considered as the main sources of the nucleonic Galactic CRs.

If CRs in SN 1006 are produced due to the diffusive shock acceleration process, then even in the case of inefficient proton injection quite a large but plausible downstream magnetic field $B_{\rm d} \approx 13$ μG is required to fit the data. It is several times larger than assumed in a simple estimate by Tanimori et al. [18], because the shock produces in this case an electron spectrum $N_{\rm e} \propto \epsilon_{\rm e}^{-2}$ which is significantly harder than the spectrum assumed in that estimate.

As it is illustrated in Fig.1, the existing SNR data are better approximated if a significantly larger downstream magnetic field value $B_d = 120$ μG and a physically much more plausible, efficient nucleon injection rate $\eta = 2 \times 10^{-4}$ is assumed. Such an ion injection rate is estimated from injection theory, and consistent with the observed radio spectral index $\alpha = 0.57$.

We find that after adjustment of the predictions of the nonlinear spherically-symmetric model by a renormalization of the number of accelerated nuclear CRs with $f_{\rm re} = 0.2$ to take account of the large area of quasiperpendicular shock regions in a SNR, good consistency with all observational data can be achieved, including the reported TeV γ-ray flux. As it is seen in Fig.2 the π^0-decay γ-ray flux produced by the nuclear CR component exceeds the flux of IC γ-rays gener-

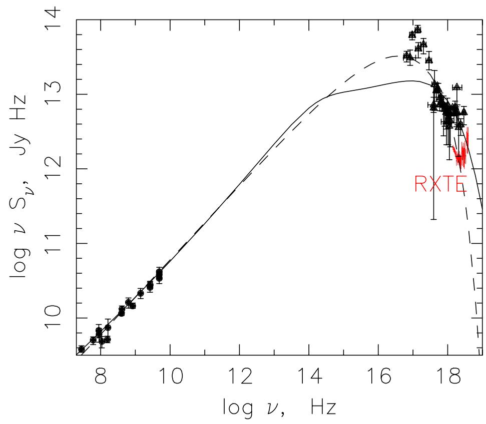

Fig. 1. Synchrotron emission flux of SN 1006 as a function of frequency. Solid and dashed lines correspond to efficient and inefficient proton acceleration, respectively [14]. The observed X-ray [15,16] and radio emissions [17] are shown.

ated by the electronic CR component at all energies above about 100 MeV. Since the theory did not make use of any knowledge derived from γ-ray measurements, the reported TeV flux from SN 1006 therefore supports the idea that the nuclear CR component is indeed produced in SNRs. The π^0-decay γ-ray flux comes from two polar caps of the remnant.

The maximum energy of accelerated protons $\epsilon_{\mathrm{max}} = 3 \times 10^{14}$ eV and their total energy content $E_{\mathrm{c}} \approx 3 \times 10^{50}$ erg, reproduced in this case, are consistent with the requirements for the Galactic CR sources.

Comparing the case of efficient proton acceleration with the inefficient proton acceleration case, we see that the expected π^0-decay γ-ray flux $F_\gamma^\pi \propto \epsilon_\gamma^{-1}$ extends up to almost 100 TeV, whereas the IC γ-ray flux reaches less than about 10 TeV. Therefore the detection of γ-ray emission above 10 TeV would imply evidence for a hadronic origin.

Phenomenological studies of the γ-ray emission from SN 1006 on the basis of the observed synchrotron emission have preferred a dominance of IC emission from electrons in the γ-ray part of the emission spectrum [18]. This scenario can not explain the apparent bipolar morphology inferred from the existing γ-ray measurements and yields a much less convincing approximation to the radio and X-ray synchrotron spectrum. In addition, as we have shown, the IC emission should reach at best about 10 TeV. Apart from future detailed determinations of the γ-ray morphology one therefore needs to precisely measure the γ-ray flux at energies ϵ_γ between 100 GeV and 100 TeV, and preferably even from 100 MeV upwards. The detailed spectra and in particular the existence of γ-rays with very

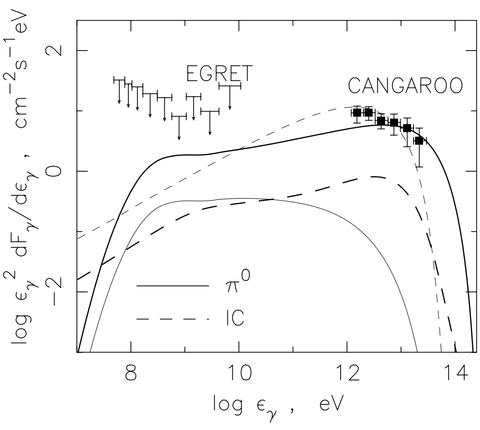

Fig. 2. Differential π^0-decay (solid lines) and IC (dashed lines) γ-ray fluxes of SN 1006 as a function of γ-ray energy [14]. Thick (thin) lines correspond to efficient (inefficient) injection/acceleration. High energy γ-ray flux data [18] and EGRET upper limits [19] are also shown.

high energies above 10 TeV should allow a confirmation, or a rejection, of CR nucleon production in SN 1006 with an acceleration efficiency that is consistent with the requirements on the Galactic CR energy budget.

It is important to note that analysis of the radial distribution of the SNR surface brightness provides the additional possibility to discriminate efficient and inefficient scenario of CR acceleration. In Fig.3 we demonstrate it for γ-ray emission at energy 3 TeV. Two points come from this figure. First is that π^0-decay emission is strongly concentrated near the SNR edge, whereas if TeV-emission is due to the electron component it has much wider distribution. Second, in the case of efficient CR production the radial distribution of electrons with energy $\epsilon \approx 30$ TeV is characterized by the sharp peak at the shock position with the width $l \approx 0.03R_s$. Taking into account that the current shock size is $R_s = 7$ pc we have $l \approx 0.2$ pc. About the same electrons produce synchrotron radiation at keV-energies. Analysis of ASCA image of SN 1006, presented by Bamba et al.[20] , which gives an average value $l = 0.2$ pc at X-ray energy range from 2 to 10 keV, provides an excellent confirmation of our efficient model, eventhough authors made a different conclusion.

We therefore conclude that the analysis of SN 1006 on the basis of overall SNR dynamics and nonlinear diffusive shock acceleration theory results in a picture where the nuclear component is strongly accelerated, consistent with all data for this SNR.

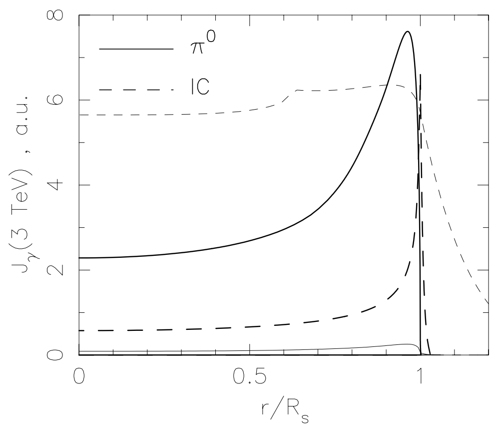

Fig. 3. Radial dependence of the γ-ray brightness of SN 1006 for the γ-ray energy $\epsilon_\gamma = 3$ TeV [14]. Thick and thin curves correspond to the high and low proton injection/acceleration efficiency, respectively.

4. Tycho's supernova remnant

The kinetic nonlinear model for CR acceleration in SNRs has been applied in detail to Tycho's SNR [21], in order to compare theoretical results with the recently found very low observational upper limit for the TeV γ-ray flux [22]. We have used stellar ejecta parameters $M_{\rm ej} = 1.4 M_\odot$, distance $d = 2.3$ kpc, and ISM number density $N_{\rm H} = 0.5$ cm^{-3}. Explosion energy $E_{\rm sn} = 0.27 \times 10^{51}$ erg was derived to fit the observed size $R_{\rm s}$ and expansion speed V_s which are determined by the ratio $E_{\rm sn}^2/N_{\rm H}$. Even though the distance to the object is not very well known, the set of parameters has been shown to be internally consistent, and the predictions for the radio the and γ-ray fluxes are quite robust with respect to different parameter values in the literature.

A rather high downstream magnetic field strength $B_{\rm d} \sim 240$ μG and a proton injection rate $\eta = 3 \times 10^{-4}$ are needed to reproduce the observed steep and concave radio spectrum and to ensure a smooth cutoff of the synchrotron emission in the X-ray region. The evidence for efficient nucleonic CR production that comes from the radio and X-ray data and leads to a strong shock modification, is even more definite for Tycho's SNR than in the case of SN 1006.

We find that, after adjustment of the predictions of the nonlinear spherically-symmetric model by a physically necessary renormalization of the number of accelerated CR nuclei to take account of the quasi-perpendicular shock directions in a SNR, quite a reasonable consistency with most of the observational data can be achieved. The resulting nonthermal electron to proton ratio turns out to be consistent with the observed ratio in interstellar space. The total γ-ray flux at

1 TeV (with the π^0-decay component exceeding the IC component) comes out to be slightly lower than the most restrictive observational upper limit from the HEGRA experiment. It leads us to the prediction that detectors with several times higher sensitivity, like MAGIC or VERITAS in the Northern Hemisphere, should indeed detect this source above 100 GeV in γ-rays.

The expected π^0-decay γ-ray flux $F_\gamma^\pi \propto \epsilon_\gamma^{-1}$ extends up to $\sim$ 30 TeV, whereas the IC γ-ray flux has a cutoff above a few TeV. Therefore the detection of γ-ray emission at $\sim$ 10 TeV would in addition imply clear evidence for a hadronic origin.

5. Supernova remnant Cassiopeia A

Cassiopeia A is a prominent shell type supernova remnant, and a bright source of synchrotron radiation observed at radio frequencies and most probably also in the X-ray band [23]. With the synchrotron interpretation, the measured hard X-ray emission is direct evidence for the existence of a large number of relativistic electrons with energies up to about 10 TeV, presumably accelerated at the shock. If protons are accelerated in Cas A to at least the same energy and as efficiently as electrons then the π^0-decay γ-ray spectrum, created in their hadronic collisions with the background nuclei, should extend to energies above 1 TeV with a hard power-law. The detection of a signal in TeV γ-rays has been indeed recently reported by the HEGRA collaboration [24]. Therefore it is of the exceptional importance to find out whether this γ-ray emission is consistent with a hadronic origin.

To describe the circumstellar medium [25] we used the specific model of Borkowski et al.[26]. Accordingly, part of the slow red supergiant wind of the SN progenitor has been swept up into a dense shell by a fast stellar wind during the final blue supergiant (probably Wolf-Rayet) phase of the progenitor star. Therefore the inner circumstellar medium consists of three zones: a tenuous wind-blown bubble, a dense shell, and a freely expanding red supergiant wind. The outer regions due to the main sequence evolution play no role here.

Perhaps the most important result of our considerations is that the spectral shape of shock accelerated electrons with their essential synchrotron cooling in the downstream region is very well consistent with the observed synchrotron emission. To reproduce a very steep radio spectrum $S_\nu \propto \nu^{-0.77}$ the shock must be strongly modified. This shock modification can only be produced by accelerated protons if they are also efficiently injected ($\eta = 2.5 \times 10^{-3}$) into the acceleration process, as it was assumed in the calculation.

The significant synchrotron losses of electrons in the strong interior mag-

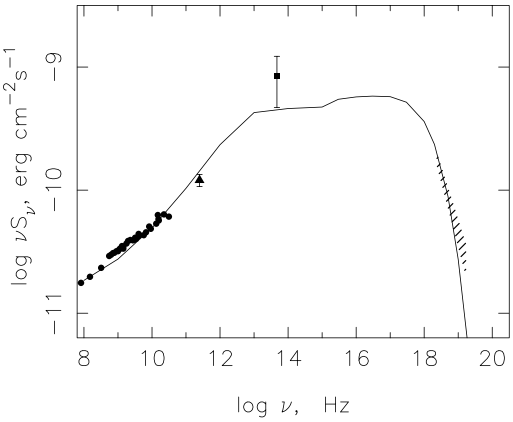

Fig. 4. Synchrotron spectral energy distribution of Cas A as a function of frequency at epoch 1970 [25]. The radio-emission above 100 MHz [27] the data at 1.2 mm (triangle) [28] and 6 μm (square) [29] as well as the hard X-ray spectrum [23] are presented.

netic field $B_d \approx 1$ mG makes their spectrum steep $N_\mathrm{e} \propto \epsilon_\mathrm{e}^{-3}$ also at high energies $\epsilon_\mathrm{e} > 10\,\mathrm{GeV}$. This leads to a flat connection of the spectral energy distributions of the observed radio and X-ray synchrotron emissions (see Fig.4).

The rather high secular decline of the synchrotron radiation observed in the radio range is naturally reproduced in our model due to the dominant role of electrons accelerated at a previous epoch and currently undergoing adiabatic and synchrotron cooling in the expanding downstream region.

We find that after reduction of the predictions of the nonlinear spherically-symmetric model by a renormalization of the number of accelerated nuclear CRs, to take account of the large areas of quasiperpendicular shock regions of a SNR, good consistency with all observational data can be achieved, including the reported TeV γ-ray flux (see Fig.5). The used renormalization factor $f_{re} = 1/6$ is consistent with the need that the average acceleration efficiency of a typical SNR within our model scenario should meet the requirements for Galactic CR acceleration.

In addition, our calculations show that at all energies above 1 GeV the γ-ray production is dominated by π^0-decay. At TeV energies the expected π^0-decay flux exceeds the IC and nonthermal bremsstrahlung (NB) fluxes by a factor of about seventy. Therefore the leptonic emission is totally inadequate to explain the observed TeV γ-ray flux. The π^0-decay spectrum $F_\gamma^\pi \propto \epsilon_\gamma^{-1}$ extends up to 30 TeV, whereas the IC and NB γ-ray fluxes have a cutoff at about 1 TeV. Therefore the detection of γ-ray emission at 10 TeV and above would imply further evidence for its hadronic origin.

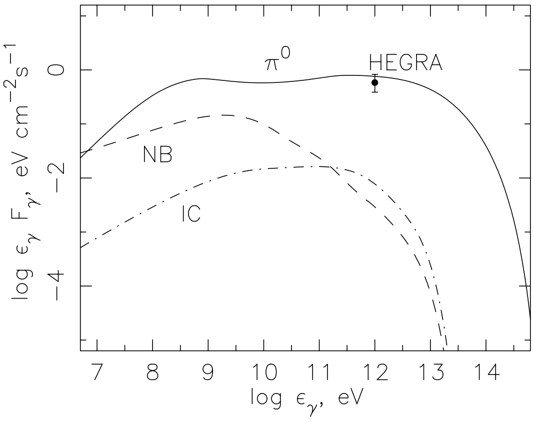

Fig. 5. Bremsstrahlung (dash-dotted), IC (dashed) and π^0-decay (solid) integral γ-ray energy fluxes of Cas A as a function of γ-ray energy [25]. The 1 TeV data point is from HEGRA [24].

We conclude that the observed properties of the radio and X-ray emission can be explained within the assumption that the SN blast wave is the main source of energetic particles in Cas A. The CR production efficiency and the electron to proton ratio implied by these multi-wavelength observations are consistent with the requirements of the nuclear CR sources in the Galaxy.

6. Summary

Detailed consideration performed within a frame of nonlinear kinetic model demonstrates, that the CR production efficiency in young SNRs is consistent with requirements of GCR sources in the Galaxy.

Synchrotron radiation from young SNRs provide the evidence that efficient CR acceleration followed by the essential shock modification and magnetic field amplification takes place there.

It is shown that the kinetic nonlinear theory fits the existing data in a satisfactory way within set of parameters consistent with the idea that all these SNRs are typical sources of Galactic CRs. A rather high interior magnetic field is required to give a good fit for the radio and X-ray synchrotron radiation. In all cases π^0-decay γ-rays generated by the nuclear component dominates over γ-rays, generated by electron component.

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