A NEW MODEL FOR THE THERMAL X-RAY COMPOSITES AND THE PROTON ORIGIN $\gamma$-RAYS FROM SUPERNOVA REMNANTS

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Abstract Recent nonthermal X-ray and $\gamma$-ray observations, attributed to electron emission processes, for the first time give an experimental confirmation that electrons are accelerated on SNR shocks up to the energy $\sim 10^{14}$ eV. We have no direct observational confirmations about proton acceleration by SNR. Different models of $\gamma$-emission from SNRs predict different emission mechanisms as dominating. Only $\pi^o$ decays created in proton-nucleon interactions allow us to look inside the CR nuclear component acceleration processes. A new model for the thermal X-ray composites strongly suggest that thermal X-ray peak inside the radio shell of SNR tells us about entering of one part of SNR shock into a denser medium compared with other parts of the shell. This makes a TXCs promising sites for $\gamma$-ray generation via $\pi^o$ decays. Detailed consideration of SNR-cloud interaction allows to increase an expected proton induced $\gamma$-ray flux from SNR at least on an order of magnitude, that allows to adjust the theoretical $\pi^o$ decay $\gamma$-luminosities with observed fluxes at least for a few SNRs even for low density ($n_o \sim 10^1 \div 10^2$ cm$^{-3}$) cloud.

1 Introduction

Since SNRs possess high enough energy, their shocks are belived to be a major contributor of both electron and nuclear components of Galactic CRs up to energies $10^{15}$ eV. SNRs emit in all wavelengths. Their radio emission gives clear evidence about relativistic electrons accelerated on the shock front. Observed nonthermal X-ray emission from several SNRs (SN 1006, Cas A, Tycho, G347.3-0.5, IC443, G266.2-1.2) is thought to be also synchrotron, from the shock accelerated electrons with a much higher energy ($\sim 10^{13}$ eV). Observed synchrotron X-ray and TeV $\gamma$-ray emission from SN 1006 as well as from G347.3-0.5, by attributing the emission to the synchrotron radiation, gives firm confirmations that electrons are accelerated on the SNR shocks up to energies $\sim 10^{14}$ eV. The theory of acceleration
of CRs on the shock front via the first order Fermi mechanism predicts that
the number of electrons $N_e$ involved in the acceleration process is much smaller
than the number of protons $N_p$: $N_e(\varepsilon)/N_p(\varepsilon) = (m_e/m_p)^{(\alpha-1)/2} \approx 10^{-2}$ ($\alpha$ is the spectral index of accelerated particles, $\varepsilon$ is the energy of particles). Thus, if there are electrons accelerated to such high energies, we should expect that protons with the same high energy have to reveal themselves in observations, too. We have to look for the objects which might emit $\gamma$-rays mainly via neutral pion decays.

2 Observations of the $\gamma$-rays from SNRs

The visibility of SNRs in Gev and TeV $\gamma$-rays was treated in [8, 1]. The main conclusion from the theory is: if SNRs are mainly responsible for the galactic CRs, it may be difficult to observe SNRs by EGRET, but should be possible to detect compact (with angular size $\sim 0.25'$) remnants from a distance less than several kpc in TeV band, with Cherenkov telescopes. Unfortunately, as first results on TeV $\gamma$-observations as well as most of the next (G78.2+2.1, W28, IC 443, $\gamma$-Cygni, W44, W63, Tycho; see short review in [25]) have given a negative result. Till now TeV $\gamma$-rays were observed from only two SNRs.

SN 1006 is the first shell-like SNR detected as a TeV source. Whereas authors in [33] attributed this emission to synchrotron, the emission is tried to be explained by other mechanisms, too. Recent discussion on the origin of TeV $\gamma$-rays form SN 1006 [2] shows that a proton origin of $\gamma$-rays is possible if distance to the remnant is about 1 kpc and there is a significant compression of gas. Nevertheless other emission mechanisms may not be excluded (see, e.g. [21]). The observations of G347.3-0.5 reported recently also reveal a TeV $\gamma$-flux. Authors attributed this emission to inverse Compton scattering of CMBR by shock accelerated electrons and estimate $\pi^0$ induced contribution as too low, but did not exclude it because of possibility of interactions with a cloud [28].

The first [9], second [34] and the third [11] EGRET catalogue of the high-energy $\gamma$-ray sources among the general categories (solar flare, pulsars, $\gamma$-ray bursts, radio galaxy, active galactic nuclei and blazars), include lists of sources for which no identification with objects at other wavelengths is yet surely found. The analysis of possible associations of the SNR positions with error circles of the unidentified $\gamma$-sources was first performed in [31]. Analysis of unidentified sources from the third EGRET catalog [23] shows 22 such possible associations with probability of being of chance less than $10^{-5}$. Some other unidentified EGRET sources might be related to yet undetected SNR. Of course, a part of these remnants have or may have their compact stellar remnants, pulsars, which can be responsible for the $\gamma$-ray emission. There are 225 known SNRs in our Galaxy [10]. The short history of studies on association of EGRET sources with SNRs may be found in [23].

Up to now, there is no clear observational confirmation that nuclear component of CRs is generated by SNRs. There is only one observation reported as
confirmation of this thought\cite{7}. The nature of $\gamma$-emission in all observations is very questionable.

There are several emission processes in competition in analysis of observed SNR $\gamma$-ray spectra. It depends on the conditions in emission site and on the way to the observer which one will dominate. It is well known that we should have a high number density of target nuclei in order to make the $\pi^0$ decay mechanism dominate in a model. Therefore, $\gamma$-rays from proton-proton collisions are expected from the SNRs which are located near the dense interstellar material and reveal evidence about interaction with it.

3 Thermal X-ray composites. A new model in 3 dimensions

To look for signatures of proton acceleration in SNR, it is interesting to consider a mixed-morphology class of SNRs which is known also as thermal X-ray composites (TXCs). These are remnants with a thermal X-ray centrally filled morphology within the radio-brightened limb. Such remnants were first reviewed in\cite{21}. The authors of\cite{22} argued that they create a separate morphological class of SNR. It is interesting that most of these SNRs reveal observational evidence about the interaction with nearby molecular clouds. There are 7 remnants in the analysis of association of the 2EG sources with SNRs\cite{12}. Four of them (W28, W44, MSH 11-61A, IC443) belong to the class mentioned and interact with clouds.

The authors of\cite{22} have emphasized two prominent morphological distinctions of TXCs: a) the X-ray emission is thermal; the distribution of X-ray surface brightness is centrally peaked and fills the area within the radio shell, b) the emission arises primarily from the swept-up ISM material, not from ejecta. Besides similar morphology, the sample of SNRs also has similar physical properties\cite{22,20}. Namely, i) the same or higher central density compared to the edge, ii) complex interior optical nebulosity, iii) higher emission measure in the region of X-ray peak localisation, iv) temperature profiles are close to uniform. Seven objects from the list of 11 TXCs interact with molecular clouds\cite{22}. Thus, ambient media in the regions of their location are nonuniform and cause a nonsphericity of SNRs.

Two physical models have been presented to explain TXC (see review in\cite{22,20}). These models are used to obtain the centrally filled X-ray morphology within the framework of one-dimensional (1-D) hydrodynamic approaches. When we proceed to 2-D or 3-D hydrodynamical models, we note that a simple projection effect may cause the shell-like SNR to fall into another morphology class, namely, to become TXC\cite{14}. The main feature of such a SNR is the thermal X-rays emitted from the swept-up gas and peaked in the internal part of the projection. Densities over the surface of a nonspherical SNR may essentially differ in various regions. If the ambient density distribution provides a high density in one of the regions across the SNR shell and is high enough
to exceed the internal column density near the edge of the projection, we will see a centrally filled X-ray projection. Thus, this new model strongly suggests that the thermal X-ray peak inside the radio shell tells us that one part of SNR shock has entered into a denser medium compared with other parts. This makes TXCs promising sites for γ-ray generation via π⁰ decays.

4 SNR γ-rays from decay of neutral π-mesons

Whereas astrophysical realisations of several emission mechanisms allow us to make conclusions about acceleration of CR electron component on the shock fronts of SNRs, only π⁰ decay γ-rays give us the possibility to look at the proton component acceleration processes having data in ε, ≥ 100 MeV.

4.1 Estimations on the π⁰ decay γ-ray luminosity

Luminosity of an SNR in π⁰ decay γ-rays in ε ≥ ε, min/6 band is \( \frac{c \sigma_{pp}}{6} n_N W_{cr} \).

\( L_{\gamma} = \frac{c \sigma_{pp}}{6} n_N W_{cr} \)  \( (1) \)

where \( \varepsilon_{\text{min}} \approx 600 \text{ MeV} \) is the minimal proton kinetic energy of the effective pion creation, cross section \( \sigma_{pp}(\varepsilon) \) is close to the mean value \( \sigma_{pp} = 3 \cdot 10^{-26} \text{ cm}^2 \), \( n_N \) is the mean number density of target nuclei and \( W_{cr} \) is the total energy of cosmic rays in the SNR with \( \varepsilon \geq \varepsilon_{\text{min}} \). There are different estimations of the efficiency \( \nu \) of the flow’s kinetic energy transformation into the energy of accelerated particles: \( W_{cr} = \nu E_o \). We take acceptable value \( \nu = 0.03 \). Thus, in the first approach, the theoretical estimation on the π⁰ decay γ-luminosity of any SNR is

\( L_{\gamma} \geq 100 \gamma = 6.3 \cdot 10^{33} n_o \nu_3 E_{51} \text{ erg/s} \),

where \( \nu_3 = \nu/0.03 \), \( E_{51} \) is the energy of supernova explosion \( E_o \) in the units of \( 10^{51} \text{ erg} \), \( \pi_o = \pi_{o,N}/1.4 \) is the average hydrogen number density within SNR which equals to average hydrogen number density of the ambient medium in the region of an SNR location, in cm\(^{-3}\).

The real situation is more complicated. Often only a part of SNR interacts with a denser ISM material. There are factors which increase CR energy density \( \omega_{cr} \)[13]: 1) The CRs are not uniformly distributed inside an SNR; most of CRs are expected to be in a thin shell near the shock front where most of swept-up mass is concentrated. 2) The reverse shock from interaction with dense cloud also increases the energy density of CRs. These factors enhance \( \omega_{cr} \) in the region of interaction \( \[3\] \):

\( \omega_{cr} \approx 1.7 \left( \frac{\gamma}{\gamma - 1} \right)^{3/2} \overline{\omega}_{cr} \),

where CR energy density in the region of interaction is \( \omega_{cr} = W_{cr}/V_{int} \) and \( \overline{\omega}_{cr} = W_{cr}/V_{snr} \). This gives \( \omega_{cr} \approx 6.6 \overline{\omega}_{cr} \) for \( \gamma = 5/3 \).
If we put $W_{cr} = \omega_{cr} V_{int}$ into (1), we obtain with (2) that for any SNR

$$L^{100}_\gamma = 1.7 \cdot 10^{35} \eta \nu_5 E_{51} \text{ erg/s}$$

(3)

where $\eta = V_{int}/V_{snr}$, $n_o$ is the number density of the ambient medium before the shock wave in the region of interaction, $\gamma = 5/3$. We have to take into account that region of interaction is not extended to the region before the shock, since the energy density of CR should be considerably lower outside the SNR [5, 13].

It is easy to estimate $\eta$ following the consideration in [13]:

$$\eta = 0.18 \mu^2 \sqrt{\xi}, \quad \mu \leq 0.2,$$

(4)

where $\xi = n_o/\pi_o$, $\mu = R_{int}/\bar{R}$, $R_{int}$ is the average radius of the surface of interaction, $\bar{R}$ is the average radius of SNR.

Thus, considering the hydrodynamic process of SNR-cloud interaction in details, it is possible to increase the expected $\pi^0$ decay $\gamma$-ray flux by $26 \eta \xi \simeq 0.2 \xi^{3/2}$ times, i.e., up to few orders of magnitude. This is enough e.g. for explanation of TeV $\gamma$-rays from SN1006 as a result of decays of neutral pions [33]. Additional factor increasing the effectivity of $\pi^0$ meson production is instability of contact discontinuity between the SNR and the cloud material which mixes the media with high energy particles and target nuclei [13]. This factor should also be considered in future.

4.2 Nucleonic origin $\gamma$-rays from MSH 11-61A

SNR G290.1-0.8 (MSH 11-61A) is located in the southern hemisphere. The distance to the remnant, 7 kpc, is obtained from the optical observations [24], but not yet confirmed by X-ray observations [30]. X-ray and radio morphologies [27, 35] make the SNR a member of TXC class. In the direction to MSH 11-61A lies the $\gamma$-ray source 2EG 1103-6106 (3EG J1102-6103) [32, 23]. Is it possible to consider observed flux of the EGRET source directed toward the MSH 11-61A as $\pi^0$ decay $\gamma$-ray emission?

The $\gamma$-flux from the source 2EG 1103-6106 in the EGRET band $\varepsilon_\gamma = 30 \div 2 \cdot 10^4$ MeV is approximated as [18]

$$S_\gamma = (1.1 \pm 0.2) \cdot 10^{-9} \left( \frac{\varepsilon_\gamma}{213 \text{ MeV}} \right)^{-2.3\pm0.2} \text{ photon cm}^2 \cdot \text{s} \cdot \text{MeV}^{-1}.$$ 

Thus, the luminosity of the source in $\varepsilon_\gamma \geq 100$ MeV band is respectively

$$L^{100}_{\gamma, \text{obs}} = 4 \cdot 10^{34} d_{\text{kpc}}^2 \text{ erg/s}.$$ 

Most recent study on MSH 11-61A [30] gives the parameters of the object presented in Table 1 (different for different distance assumed). There are also values of $\xi$ in the table which allow to adjust the expected luminosity of MSH 11-61A in $\pi^0$ decay $\gamma$-rays with observed flux from the source 2EG 1103-6106. We see that moderate number density $\sim 150$ cm$^{-3}$ of cloud located near the one region of the remnant is enough to explain the luminosity of 2EG 1103-6106,
Table 1: Parameters of MSH 11-61A [30], luminosity $L_{\gamma,\text{obs}}^{\geq 100}$ of 2EG 1103-6106 and estimations on the proton origin $\gamma$-luminosity of the SNR. Presented values of $\xi$ allow us to satisfy condition $L_{\gamma,\text{obs}} = L_{\gamma}$.

| $d$, kpc | Age $t$, $10^4$ yrs | $\pi_51$, $10^{51}$ erg | $\pi_{\pi}$, cm$^{-3}$ | $L_{\gamma,\text{obs}}^{\geq 100}$, $10^{36}$ erg/s | $L_{\gamma,\text{obs}}^{\geq 100}/\xi^{3/2}$, $10^{32}$ erg/s | $\xi$, $10^2$ |
|----------|-------------------|-----------------|----------------|-------------------|------------------|----------|
| 10       | 1.3               | 18              | 1              | 0.27              | 4                | 3.2      | 5        |
| 7        | 0.9               | 13              | 0.4            | 0.27              | 2                | 1.3      | 6        |

by protons accelerated on the shock front of MSH 11-61A. Note, if we take $\nu \simeq 0.1 - 0.2$ [1] instead of the value used here, $\nu = 0.03$, the density of cloud needs to be only $\sim 20 \div 40$ cm$^{-3}$. It is interesting that the same consideration allows also to adjust the $\pi^o$ decay $\gamma$-luminosity of the source 2EG J0618+2234 (3EG J0617+2238) directed toward IC 443 with the luminosity of this SNR [13].

5 Conclusions

We may expect that nucleonic component of CRs accelerated on SNR shocks have to reveal itself in observations. Which SNRs might emit $\gamma$-rays mainly via neutral pion decays? Presented model for TXCs makes the members of this class very promising candidates for the $\pi^o$ decay $\gamma$-ray sources since a central thermal X-ray peaked brightness might be evidence for density gradient and high density in one of the regions before SNR shock. CR distribution inside SNR is not uniform; most of CR should be confined in a relatively thin SNR shell. CRs are accelerated not only by the forward shock, but also by the reverse one. Consideration of these factors causes an enhancement of the $\pi^o$ decay $\gamma$-ray flux of at least on an order of magnitude. This allows us to adjust the theoretical flux with observed one in at least few cases. So, we have enigmatic situation. There are the class of prospective sources. Theory can fit the $\pi^o$ decay $\gamma$-ray fluxes. Why we do not have many direct observations of such $\gamma$-rays in order to confirm theoretical predictions about CR generation by SNRs? The question remains open.

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