The very high energy characteristics of shell-type SNRs and Pulsar Wind Nebulae at different ages

V G Sinitsyna, A Y Alaverdyan, M S Andreeva, K A Balygin, S S Borisov, I A Ivanov, A M Kirichenko, A I Klimov, I P Kozhukhova, R M Mirzafatikhov, N I Moseiko, S I Nikolsky, I E Ostashov, A I Palamarchuk, V Y Sinitsyna, I G Volokh

P.N. Lebedev Physical Institute, Leninsky pr. 53, Moscow, Russia
E-mail: sinits@sci.lebedev.ru

Abstract. The investigation of VHE gamma-ray sources by any methods, including mirror Cherenkov telescopes, touches on the problem of the cosmic ray origin and, accordingly, the role of the Galaxy in their generation. The SHALON observations have yielded the results on Galactic supernova remnants of shell-type and Pulsar Wind Nebulae of different ages. For each of SNRs the observation results are presented with spectral energy distribution by SHALON in comparison with other experiment data and images by SHALON. The data obtained suggest that the very high energy $\gamma$-ray emission in the objects being discussed is different in origin.

Introduction

The SHALON observations have yielded the results on of two types of Galactic supernova remnants (SNR) of different ages. Among them are: the shell-type SNRs Tycho's SNR, Cas A, IC 443, $\gamma$Cygni SNR and the plerions Crab Nebula, 3C58, Geminga (probably plerion) as well as the classical nova GK Per that is on the earliest SNR evolution stage. For each of SNRs the observation results are presented with spectral energy distribution by SHALON ($\Delta$ and $\▲$) in comparison with other experiment data and images by SHALON (color scale) in comparison with data from X-ray and radio-data. Also the theoretical predictions is shown. The collected experimental data can help to solve the cosmic ray origin.

GK Per (Nova 1901)

Nova Persei 1901 (GK Per) is one of the most extensively studied classical nova shells over the entire electromagnetic spectrum. Remnant of nova is detected at radio energies with the Very Large Array as a source of nonthermal, polarized radio emission [1]. These observations show the existence of shocked interstellar material. The X-ray shell around GK Per was first discovered with the ROSAT experiment and then it has been observed by Chandra telescope [2]. The X-ray emission of the same electron population has been detected with Chandra as the extension from the radio wavelengths. The detection of the X-rays from the supernova remnant shell which are primarily due to bremsstrahlung of shock accelerated relativistic electrons, supposed the detection of $\gamma$-ray emission originated from $\pi^0$- decay, secondary pp-interactions [3] as well as possible contribution emission produced via Inverse Compton (IC) scattering [3]. Chandra X-ray
Table 1. The catalogue of galactic γ-ray sources by SHALON with parameters for spectrum fitting in form of power low with exponential cutoff $F(E) \propto E^{k_\gamma} \times \exp(-E/E_{\text{cutoff}})$.

| Sources          | Observable fluxa | $k_\gamma$ | $E_{\text{cutoff}}$, TeV | Distance, kpc | Type             |
|------------------|------------------|------------|--------------------------|---------------|------------------|
| Crab Nebula      | (2.12 ± 0.12)    | -1.36 ± 0.09 | 19.0 ± 2.0               | 2.0           | PWN              |
| Geminga          | (0.48 ± 0.07)    | -0.39 ± 0.05 | 5.4 ± 1.0                | 0.25          | PSR or PWN       |
| 3C 58            | (0.36 ± 0.15)    | -1.33 ± 0.12 | -                         | 3.2           | PWN              |
| G54.1+0.3        | (0.97 ± 0.35)    | -1.43 ± 0.14 | -                         | 6.2           | PWN              |
| Tycho’s SNR      | (0.52 ± 0.04)    | -0.93 ± 0.09 | 35.0 ± 5.0               | 3.1           | Shell-type SNR   |
| Cas A            | (0.64 ± 0.10)    | -0.91 ± 0.11 | 10.3 ± 2.5               | 1.5           | Shell-type SNR   |
| IC 443           | (1.69 ± 0.58)    | -1.94 ± 0.16 | -                         | 4.5           | Shell-type SNR   |
| G166.0+4.3       | (1.07 ± 0.46)    | -1.95 ± 0.44 | -                         | 1.5           | Shell-type SNR   |
| γCygni SNR       | (1.27 ± 0.11)    | -0.93 ± 0.09 | 20.1 ± 4.2               | 0.46          | Classical Nova   |
| GK Per           | (0.31 ± 0.14)    | -1.90 ± 0.36 | -                         | 10.0          | HMX Binary       |
| Cyg X-3          | (0.68 ± 0.04)    | -1.15 ± 0.08 | 75.0 ± 10.2              | 6.0           | LMX Binary       |
| 4U 2129+47       | (0.19 ± 0.06)    | -0.42 ± 0.12 | 10.0 ± 3.0               | 6.6           | LMX Binary       |
| Her X-1          | (0.45 ± 0.18)    | -             | -                         | 0.7           | Planetary nebula |
| M57              | (0.30 ± 0.17)    | -             | -                         |               |                  |

aIntegral flux at energy > 800 GeV in units of $10^{-12}$ cm$^{-2}$ s$^{-1}$

The γ-ray source associated with the GK Per was detected above 2 TeV by SHALON with a statistical significance 9.2σ determined by Li&Ma method [4]. The representative results on GK Per fluxes, spectral energy distribution, detailed images are shown in Fig. 1 and detailed analysis of data is presented within these Proceedings and [5]. Two TeV γ-ray emission regions were revealed: the main one coinciding with the position of central source of GK Per and the weak emission of shell, that is also observed in X-ray by Chandra [2] (Fig. 1, right, red lines).

Cas A supernova remnant (1680 year)
Cas A is a youngest of historical supernova remnant in our Galaxy. Cas A was observed with SHALON during the 74 hours in period of 2010 - 2014 yy [6, 7]. The γ-ray source associated with the Cas A was detected above 800 GeV at the level of 18.1σ (the γ-ray flux and spectrum details see table 1 and [7]). Fig. 1, left presents spectral energy distribution of the γ-ray emission from Cas A by SHALON (▲) in comparison with theoretical predictions [9, 10] and other experimental data (see refs in [6, 7]). Fig. 1 right presents Chandra X-ray image of Cas A (red lines) [8] in comparison TeV structure in energy range of 0.8 - 30 TeV by SHALON.

The γ-ray emission in Cas A could be produced via IC scattering and by accelerated cosmic ray hadrons through interaction with the interstellar gas and then $\pi^0$- decay. Solid lines at Fig. 1 show the very high energy γ-ray spectra of hadronic origin [9, 10]. It was shown in [9] that leptonic model with $B = 0.3$ mG predicts a 5 - 8 times lower γ-ray flux than the observed; the model with $B = 0.12$ mG, which can broadly explain the observed GeV flux predicts the TeV spectrum with cut-off energy about 10 TeV. The detection of γ-ray emission at 5 - 30 TeV and the hard spectrum below 1 TeV would favor the $\pi^0$-decay origin of the γ-rays in Cas A.

Tycho’s Supernova Remnant (1572 year)
Tycho’s SNR originated from the Ia type supernova which exploded in 1572 year. The supersonic expansion of the stellar debris visible in of Tycho’s SNR by Chandra has created two X-ray emitting shock waves - one moving outward into the interstellar gas, and another moving back into the debris. Such the character of displacement of the shock and the contact discontinuity surfaces makes the cosmic ray acceleration at the supernova shock very efficient.
In observations of 1996 year a new galactic source was detected by SHALON [11] in TeV energies with $17\sigma$ determined by [4]. This object was identified with Tycho’s SNRs. Tycho’s SNR was also confirmed with VERITAS in observations of 2008 - 2010 years. The $\gamma$-ray emission from Tycho’s SNR was detected with Fermi LAT in the range 400 MeV - 100 GeV. The expected flux of $\gamma$-quanta from $\pi^0$-decay, extends up to $>30$ TeV, while the flux of $\gamma$-rays originated from the IC scattering has a sharp cut-off above the few TeV, so the detection of $\gamma$-rays with energies up to 80 TeV by SHALON [6] (Fig. 1) is an evidence of their hadronic origin. Also, the information on such parameters of the Tycho’s SNR as the distance (3.1 - 3.3 kpc) and interstellar medium density was obtained from the SHALON data within the nonlinear kinetic model [12]. The same parameters have obtained in [13] calculations of structures visible by Chandra at X-ray energies (see red contours in Fig. 1).

$\gamma$Cygni SNR (age $\sim (5 \div 7) \times 10^3$ years)
$\gamma$Cygni SNR is a shell-type supernova remnant, its shell-like features are known in radio- and X-ray energy regions [14]. $\gamma$Cygni SNR is older then Cas A and Tycho’s SNR, its age is estimated as 5000 - 7000 years [14] and its supposed to be and in an early phase of adiabatic expansion.

During the observations of Cyg X-3 (since 1995) the SHALON field of view contains $\gamma$Cygni SNR as it located in Cygnus Region at $\sim 2^\circ$ SW from Cyg X-3. So due to the large telescopic field of view ($\sim 8^\circ$) the observations of Cyg X-3 is naturally followed by the observations of this SNR. As a result, $\gamma$Cygni SNR was detected above 800 GeV by SHALON (see [7, 15] and these Proceedings). TeV $\gamma$-ray emission regions correlate with the NW and SE parts of the shell visible in the radio energies by CGPS (red contours in Fig. 1).

IC 443 supernova remnant (age $\sim (3 \div 30) \times 10^3$ years)
IC 443 is a shell-type SNR with a complex shape consisting of two half-shells with different radii. IC 443 is one of the best candidates for the investigation of the connection among SNRs, molecular clouds and high- and very high energy $\gamma$-ray sources. The close placement of the dense shocked molecular clouds and detected GeV-TeV $\gamma$-ray emission [17] suggests that IC 443 can be considered as a candidate to the hadronic cosmic-ray source.

IC 443 was detected by SHALON with the integral flux above 0.8TeV [7, 16] (see table 1 and Fig. 1) with a statistical significance of 9.7$\sigma$ [4]. The favored scenario in which the $\gamma$-rays of 100 MeV - 10 TeV energies are emitted in the shell of the IC443 SNR is $\pi^0$-decay which produced in the interactions of the cosmic rays with the interstellar gas [17]. Solid line in Fig 1 shows the $\gamma$-ray spectra of hadronic origin. Inverse Compton scattering can not explain the observed IC 443 $\gamma$-ray emission as there is no bright source of seed photons in the region of the IC 443. The analysis of arrival directions of $\gamma$-rays with energies 800 GeV - 10 TeV reveal the correlation of TeV $\gamma$-ray emission maxima with MeV-GeV emission observed by Fermi LAT [17], also TeV $\gamma$-ray emission of South and South-West parts of IC 443 shell correlated with the position of swept out dense molecular cloud (see red contours by CGPS in Fig. 1 ).

Crab (1054 y.)
Crab Nebula is the Historical SNR which plays an important role in the modern astrophysics.

The observation of Crab PWN in X-rays and TeV $\gamma$-rays are closely linked and have shown the leptonic origin of very high energy $\gamma$-rays in this SNR. The TeV $\gamma$-ray spectrum of Crab by SHALON from 0.8 to 30 TeV (Fig. 2, left) is generated via IC scattering of soft, mainly optical, photons which are produced by relativistic electrons and positrons, in the nebula region around 1.5' from the pulsar (Fig. 2, right) with specific average magnetic field of about 67 $\pm$ 7nT [6, 16].
**Figure 1.** Spectral energy distributions (left) and images (right) of shell-type Supernova remnants by SHALON in comparison with other experiments (see text).

**3C 58 (age of $\sim (2 \div 5) \times 10^3$ or exploded at 1181 y.)**

3c58 is similar to the Crab Nebula on many parameters, but these two objects differ significantly in luminosity and in size at X-rays and at radio-emission. The observations of the TeV $\gamma$-rays could provide an link in the evolution of PWN from the young Crab-like stage to the older plerion stages. 3C 58 was observed by SHALON in 2011 - 2015yy. The $\gamma$-ray source associated with the 3C 58 was detected above 800 GeV for the first time by SHALON [7, 16] with a statistical
Figure 2. Spectral energy distributions (left) and images (right) of PWN Supernova remnants by SHALON in comparison with other experiments (see text). Red lines show Chandra data.

significance of $8.1\sigma$ and source characteristics shown in table 1 and Fig. 2. Recently, 3C 58 was confirmed as TeV $\gamma$-ray source with MAGIC.

Geminga (age of $\sim 3.4 \times 10^5$ years)
Geminga is the closest known pulsar to Earth. It is one of the brightest source of MeV - GeV $\gamma$-ray, but the only known pulsar that is radio-quiet. The observations of Geminga by SHALON in 1999 year had yielded the detection of $\gamma$-ray emission from this object [18] and it have been intensively studied since then. Figs 2 show the SHALON results for this $\gamma$-source [16]. Also this object it suggested to be a Geminga supernova remnant with expected age of $\sim 3.4 \times 10^5$ years. The extended VHE emission from Geminga (in SHALON, Milagro observations and Fermi LAT detection and upper imits) could arise from the PWN associated with the Geminga SNR.

Conclusion
The observation results of Galactic shell-types supernova remnants on different evolution stages GK Per (Nova 1901), Cas A, Tycho’s SNR, $\gamma$Cyg SNR and IC 443 by SHALON mirror Cherenkov telescope are presented. The TeV $\gamma$-ray emission of classical nova GK Per, that could be a shell-type supernova remnant on early evolution stage, was detected for the first time by SHALON as well as TeV $\gamma$-rays from the shell of GK Per. The experimental data have confirmed the prediction of the theory about the hadronic generation mechanism of very high energy $\gamma$-rays in Tycho’s SNR, Cas A and IC443.
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