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# Tycho's SNR as the source of cosmic rays and gamma-quanta with energy of 1 – 30 TeV in Galaxy

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The gamma-quantum emitting objects in our Galaxy are the supernova remnants and binary. The observation results of gamma-quantum sources Tycho Brage and Geminga by SHALON gamma-telescope are presented. The integral spectrum of events from the source have a power index of $k_{on}$ and the spectrum of background events, observing simultaneously with source's events have index of $k_{off}$, and the source image are presented. The energy spectra of Tycho's SNR and Geminga supernova remnant $F(E_0 > 0.8TeV) \propto E^k$ are harder than Crab Nebula spectrum. The Tycho's SNR has long been considered as a candidate cosmic ray source in Northern Hemisphere. A nonlinear kinetic model of cosmic ray acceleration in supernova remnants was used to Tycho's SNR. The expected $\pi^o$ -decay gamma-quantum flux $F_\gamma \propto E_\gamma^{-1}$ extends up to $\sim$ 30 TeV, whereas the Inverse Compton gamma-ray flux has a cutoff above a few TeV. So, the detection of gamma-rays at energies of $\sim 10 - 30$ TeV by SHALON is the evidence of hadron origin.

Tycho Brage supernova remnant has been observed by SHALON atmospheric Cherenkov telescope of Tien-Shan high-mountain observatory. This object has long been considered as a candidate to cosmic ray hadrons source in Northern Hemisphere, although it seemed that the sensitivity of the present generation of Imaging Atmospheric Cherenkov System's too small for Tycho's detection. The observations on Tien-Shan high-mountain station by SHALON had been carried out since 1992 year [1 – 4]. During this period 12 metagalactic and galactic sources have been observed. Among them are galactic sources Crab Nebula (supernova remnant), Cyg X-3 (binary), Tycho's SNR (supernova remnant), Geminga (radioweak pulsar) and 2129+47 (binary) (Table 1).

For the each source the results of observation data analysis are integral spectra of events coming from source with power index of $k_{on}$, and background events, coming simultaneously with source observation with power index of $k_{off}$, time analysis of events from source and background ones, observed simultaneously and the source images. At Table 1 and Figs. 1 – 5 the observation results of galactic gamma-sources are showed. The SHALON observation results of known gamma-source Crab Nebula (Fig. 1) are consistent with observation data of the best world telescopes. The uncertainty of gamma-quantum flux from Crab Nebula is overestimated, as it includes the difference of observational results at energy range of $10^{12} - 10^{14}$ eV using gamma-telescopes and space observation results at energy range of $10^8 - 10^{10}$ eV. Such difference can also be connected with the difference of gamma-quantum generation processes at $10^{12} - 10^{14}$ eV and X-ray energy range.

**Table 1.** The SHALON catalogue of Galactic $\gamma$-quantum sources with energy $> 0.8$ TeV

| Sources | Observable flux (cm$^{-2}$ sec$^{-1}$) | Distance (kpc) |
|---|---|---|
| Crab Nebula | $(1.12\pm0.08) \times 10^{-12}$ | 2.0 |
| Cygnus X-3 | $(0.68\pm0.07) \times 10^{-12}$ | 10 |
| Geminga | $(0.48\pm0.17) \times 10^{-12}$ | 0.25 |
| Tycho' SNR | $(0.52\pm0.09) \times 10^{-12}$ | 2.3 |
| 2129+47XR | $(0.19\pm0.09) \times 10^{-12}$ | 6 |

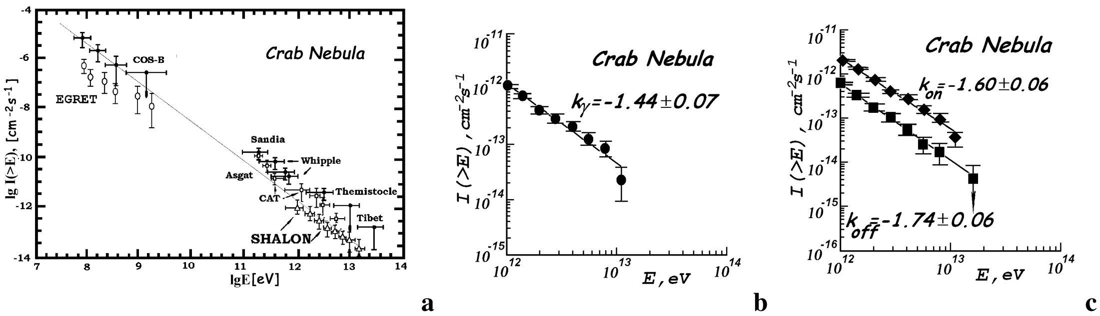


**Figure 1.** a – The Crab Nebula gamma-quantum integral spectrum by SHALON in comparison with other experiments; b – The Crab Nebula spectrum by SHALON $dF/dE_\gamma \propto E_\gamma^{-2.44\pm0.07}$; c – The spectrum of events from Crab Nebula, including $10-15\%$ contribution of background events $dF/dE \propto E^{-2.6\pm0.06}$. The spectrum of background events observed simultaneously with source $dF/dE \propto E^{-2.74\pm0.06}$.

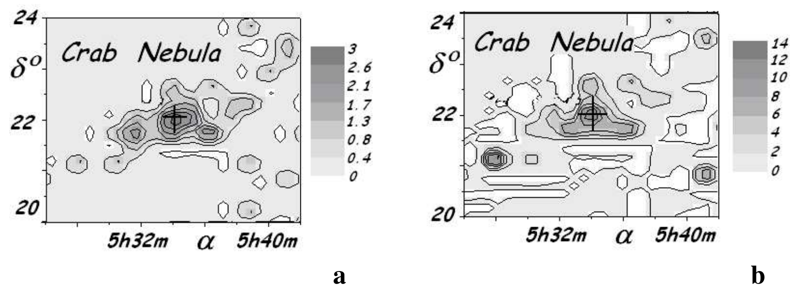


**Figure 2.** a - The Crab Nebula image at energy range of more then 0.8 TeV; b - The energy image (in TeV) of Crab Nebula by SHALON.

In Table 2 the spectrum indexes for Crab Nebula on Whipple, SHALON, CANGAROO, CAT, HEGRA atmospheric Cherenkov telescopes are presented [5]. Figures 3 and 4 show the observation results on Geminga and Tycho's SNR.

The indexes of integral spectra of events from source $k_{on}$ and background events, observing simultaneously with source's events $k_{off}$ are presented in Table 3 and Figures 3, 4 as well as the index of source integral

**Table 2.** The flux from Crab Nebula

| Group | VHE Spectrum ($10^{-11}$ photons cm$^{-2}$ s$^{-1}$ TeV$^{-1}$) | $E_{th}$ (TeV) |
|---|---|---|
| Whipple (1991) | $25 \times (E/0.4, TeV)^{-2.4\pm0.3}$ | 0.4 |
| Whipple (1998) | $(3.2 \pm 0.7) \times (E/TeV)^{-2.49\pm0.06_{stat}\pm0.04_{syst}}$ | 0.3 |
| SHALON (2003 – 2004) | $(1.7 \pm 0.26) \times 10^{-1} \times (E/TeV)^{-2.44\pm0.07}$ | 0.8 |
| CANGAROO (1998) | $(2.01 \pm 0.36) \times 10^{-2} \times (E/7, TeV)^{-2.53\pm0.18}$ | 7 |
| CAT (1999) | $(2.7 \pm 0.17 \pm 0.40) \times (E/TeV)^{-2.57\pm0.14_{stat}\pm0.08_{syst}}$ | 0.25 |
| HEGRA (1999) | $(2.7 \pm 0.2 \pm 0.8) \times (E/TeV)^{-2.60\pm0.05_{stat}\pm0.05_{syst}}$ | 0.5 |
| Tibet HD (1999) | $(4.61 \pm 0.1) \times 10^{-1} \times (E/3, TeV)^{-2.62\pm0.17}$ | 3 |

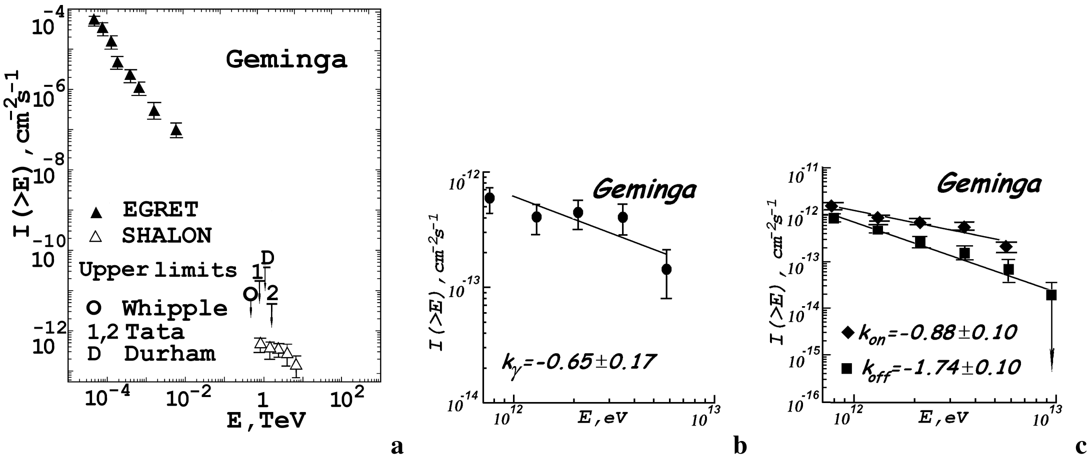


**Figure 3.** a - The Geminga $\gamma$-quantum integral spectrum by SHALON in comparison with other experiments; b- The Geminga spectrum $dF/dE_\gamma \propto E_\gamma^{-1.65\pm0.17}$; c - The spectra of events from Geminga, including 10-15% contribution of background events $dF/dE \propto E^{-1.88\pm0.10}$ and background events observed simultaneously with source $dF/dE \propto E^{-2.74\pm0.10}$.

spectrum $k_\gamma$. The energy spectra of supernova remnants Tycho's SNR and Geminga $F(E_0 > 0.8TeV) \propto E^k$ are harder than Crab spectrum.

**Table 3.** The integral spectrum indexes of SHALON spectra in SNR observations

| Sources | $k_\gamma$ | $k_{on}$ | $k_{off}$ |
|---|---|---|---|
| Tycho' SNR | $-1.00\pm0.11$ | $-1.14\pm0.06$ | $-1.73\pm0.06$ |
| Geminga | $-0.65\pm0.17$ | $-0.88\pm0.10$ | $-1.74\pm0.10$ |
| Crab Nebula | $-1.44\pm0.07$ | $-1.60\pm0.06$ | $-1.74\pm0.06$ |

A nonlinear kinetic model of cosmic ray acceleration in supernova remnants is used in Ref. [6], Fig. 5 to describe the properties of Tycho's SNR. The kinetic nonlinear model for cosmic ray acceleration in SNR has

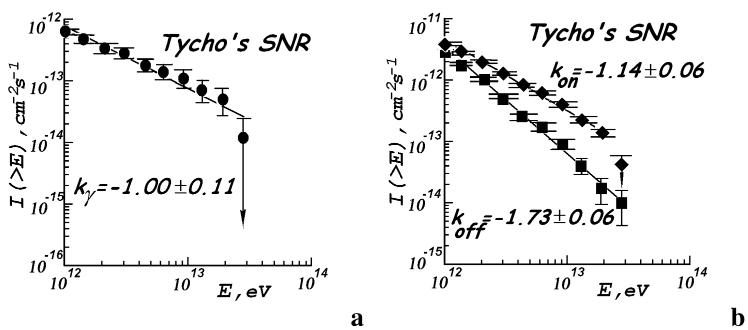


**Figure 4.** The Tycho's SNR spectrum $dF/dE_\gamma \propto E_\gamma^{-2.00\pm0.11}$; b - The spectra of events from Tycho's SNR, including 10-15% contribution of background events $dF/dE \propto E^{-2.14\pm0.06}$ and background events observed simultaneously with source $dF/dE \propto E^{-2.73\pm0.06}$.

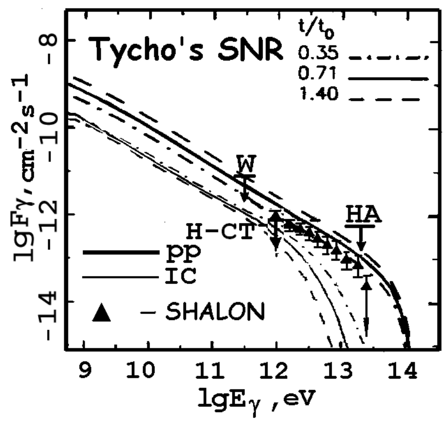


**Figure 5.** a - The Tycho's SNR integral gamma-quantum spectrum by SHALON in comparison with other experiments: the observed upper limits W – Whipple, H-CT – HEGRA IACT- system, HA – HEGRA AIROBICC and calculations [Berezhko, Völk].

been applied to Tycho's SNR in order to compare model results with recently found very low observational upper limits on TeV energy range. In fact, HEGRA didn't detect Tycho's SNR, but it could establish very low upper limit at energies $> 1$ TeV. This value is consistent with, but a factor of 4 lower than that previously published by Whipple collaboration, assuming the spectral index of $-1.1$ for comparison [6]. The $\pi^0$-decay gamma-quantum flux turns out to be some greater than inverse Compton flux at 1 TeV, dominating it strongly at 10 TeV. The predicted gamma-quantum flux is in consistent with upper limits published by Whipple [8, 9] and HEGRA [7].

The expected $\pi^0$-decay gamma-quantum flux $F_\gamma \propto E_\gamma^{-1}$ extends up to $\sim 30$ TeV, whereas the Inverse Compton gamma-ray flux has a cutoff above the few TeV. So, the detection of gamma-rays at energies of $\sim 10 - 30$ TeV by SHALON is the evidence of hadron origin [6].

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