Cosmic ray and TeV gamma-ray production in Tycho and Geminga supernova remnants

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***Abstract*— The gamma-quantum spectra produced by the electronic and hadronic components of cosmic rays have similar shapes at the energies from 1GeV to 1 TeV due to the synchrotron losses of the electrons. So, the only observational possibility to discriminate between leptonic and hadronic contributions is to measure the gamma-quantum spectrum at energies higher than 1 TeV, where these two spectra are expected to be essentially different. The gamma-quantum emitting objects in our Galaxy are the supernova remnants and binary. According to the theoretical prediction about 20 Supernova Remnants should be visible in the TeV gamma-rays whereas only two were detected up to now by SHALON, namely Tycho's SNR and Geminga. The observation results of gamma-quantum sources Tycho Brage and Geminga by SHALON gamma-telescope are presented. The energy spectra of Geminga supernova remnants and Tycho's SNR $F(E_O > 0.8TeV) \propto E^k$ are found to be harder than Crab Nebula spectrum. The expected π^O-decay gamma-quantum flux $F_\gamma \propto E_\gamma^{-1}$ extends up to ~ 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 $\sim 10-40$ TeV is the evidence of hadron origin.**

I. Introduction

TeV energies gamma-rays, measurable by the imaging Cherenkov technique, are the most interesting for searching hadronic CRs in SNRs because they provide the information about CRs of highest possible energies $10^{13}-10^{14}$ eV. Direct information about high-energy CR population in SNRs can be obtained from gamma-ray observation. The gamma-quantum spectra produced by the electronic and hadronic components of cosmic rays have similar shapes at the energies from 1GeV to 1 TeV due to the synchrotron losses of the electrons. So, the only observational possibility to discriminate between leptonic and hadronic contributions is to measure the gamma-quantum spectrum at energies higher than 1 TeV, where these two spectra are expected to be essentially different. High-energy gamma-rays are produced by electronic and hadronic CR components in the inverse Compton (IC) scattering and in the hadronic collisions leading to pion production and subsequent decay respectively. The gamma-quantum emitting objects in our Galaxy are the supernova remnants and binary. SNe of type Ib and II are more numerous in our Galaxy. According to the theoretical prediction about 20 SNRs should be visible in the TeV gamma-rays whereas only two were detected up to now by SHALON, namely Tycho's SNR and Geminga.

TABLE I
THE SHALON CATALOGUE OF GALACTIC GAMMA-QUANTUM SOURCES WITH ENERGY > 0.8 TEV

Sources	Observable flux ($cm^{-2}s^{-1}$)	Distance (kpc)
Crab Nebula (SNR)	$(1.70 \pm 0.13) \times 10^{-12}$	2
Cygnus X-3 (binary)	$(0.68 \pm 0.07) \times 10^{-12}$	10
Geminga (radioweak pulsar)	$(0.48 \pm 0.17) \times 10^{-12}$	0.25
Tycho' SNR	$(0.52 \pm 0.09) \times 10^{-12}$	2.3
2129+47XR (binary)	$(0.19 \pm 0.09) \times 10^{-12}$	6

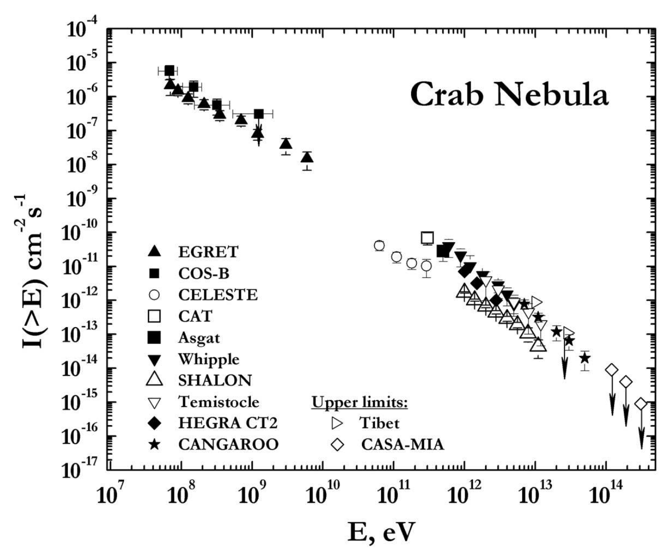

Fig. 1. The Crab Nebula gamma-quantum integral spectrum by SHALON in comparison with other experiments [1 - 12].

The observations on Tien-Shan high-mountain station with 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

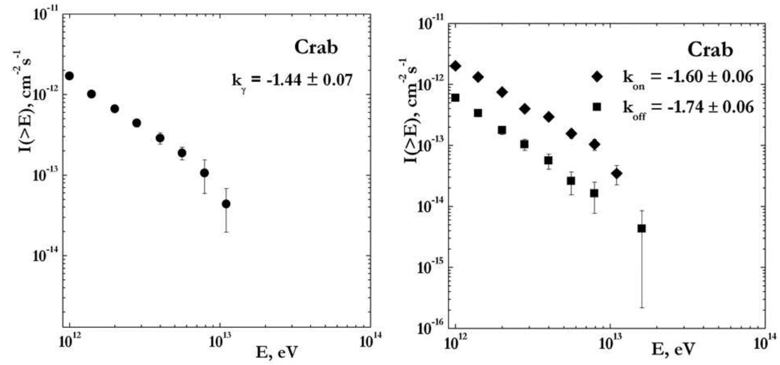

Fig. 2. left – The Crab Nebula gamma-quantum integral spectrum with power index of $k_\gamma = -1.44 \pm 0.07$; right – the event spectrum from Crab Nebula with background with index of $k_{ON} = -1.60 \pm 0.06$ and spectrum of background events observed simultaneously with Crab Nebula with index $k_{OFF} = -1.74 \pm 0.06$.

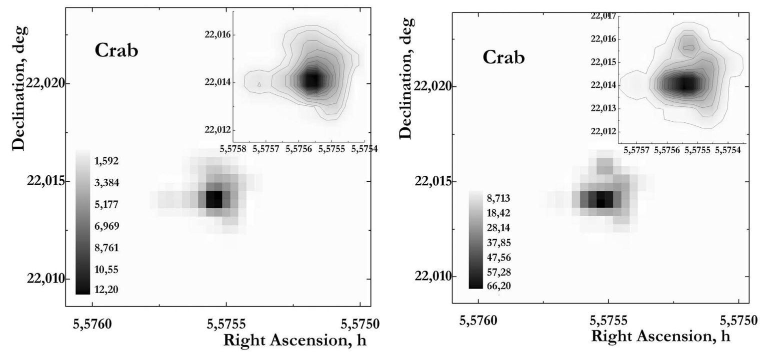

Fig. 3. left – The image of gamma-ray emission from Crab; right – The energy image (TeV units) of Crab by SHALON.

TABLE II

THE FLUX FROM CRAB NEBULA

Group	VHE Spectrum (10^{-11} $photons\ cm^{-2}s^{-1}TeV^{-1}$)	E_{th} (TeV)
Whipple (1991)	$25 \times (E/0.4TeV)^{-2.4\pm0.3}$	0.4
Whipple (1998)	$(3.2 \pm 0.7) \times (E/TeV)^{-2.49\pm0.06_{stat}\pm0.04_{syst}}$	0.3
SHALON (2005)	$(1.7 \pm 0.26) \times 10^{-1} \times (E/TeV)^{-2.44\pm0.07}$	0.8
CANGAROO (1998)	$(2.01 \pm 0.36) \times 10^{-2} \times (E/7TeV)^{-2.53\pm0.18}$	7.0
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)	$(4.61 \pm 0.1) \times 10^{-1} \times (E/3,TeV)^{-2.62\pm0.17}$	3.0

(supernova remnant), Cygnus X-3 (binary), Tycho's SNR (supernova remnant), Geminga (radioweak pulsar) and 2129+47 (binary) (Table 1). The results of observation data analysis for the each source are integral spectra of events coming from source - k_{ON}, and background events, coming simultaneously with source observation - k_{OFF}, temporal analysis of these two kind events and the source images. At Table I and Figs. 1, 2, 3, 6, 4, 5, 7, 8, 9 the observation results of Galaxy gamma-sources are showed.

II. Crab Nebula

As in many other bands of electromagnetic spectrum, the Crab Nebula has become the standard candle for TeV gamma-ray astronomy. It is available as steady source to test and calibrate the telescope and can be seen from both hemispheres. Since the first detection with ground based telescope the Crab has been observed by the number of independent groups using different methods of registration of gamma-initiated showers. Some of these detections are listed in table. II and shown on fig. 1.

The SHALON observation results of well-known gamma-source Crab Nebula (Fig. 1) are consistent with observation data of the best world telescopes. The spectrum of gamma rays from the Crab Nebula has been measured in the energy range 0.8 TeV to 11 TeV at the SHALON Alatoo Observatory by the atmospheric Cerenkov technique. The integral energy spectrum is well described by the single power law $I(>E_\gamma) \propto E_\gamma^{-1.44\pm0.07}$(Fig. 2). An image of gamma-ray emission

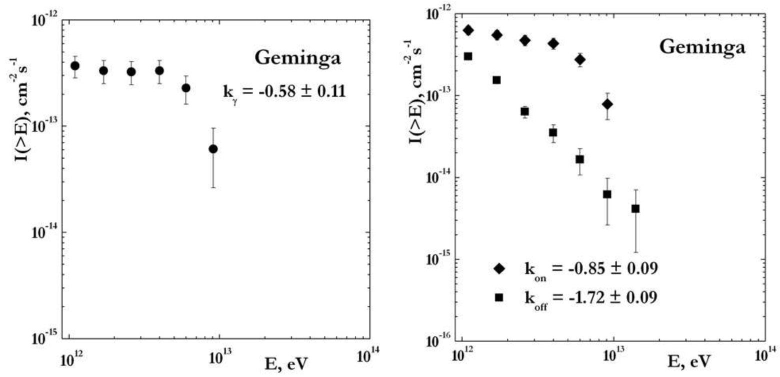

Fig. 4. left – The Geminga gamma-quantum integral spectrum with power index of $k_\gamma = -0.58 \pm 0.11$; right – the event spectrum from Geminga with background with index of $k_{ON} = -0.85 \pm 0.09$ and spectrum of background events observed simultaneously with Geminga with index $k_{OFF} = -1.72 \pm 0.09$;

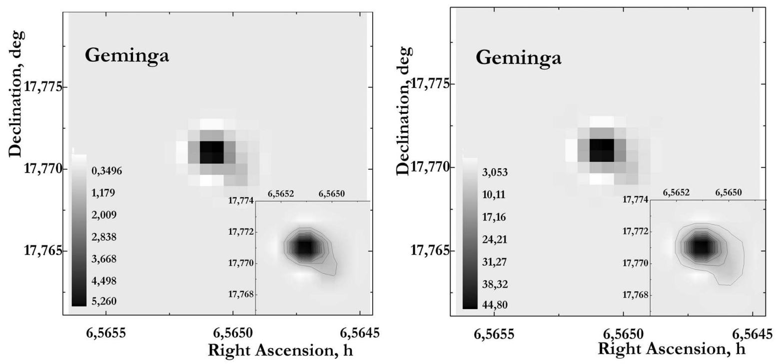

Fig. 5. left – The image of gamma-ray emission from Geminga; right – The energy image (TeV units) of Geminga by SHALON

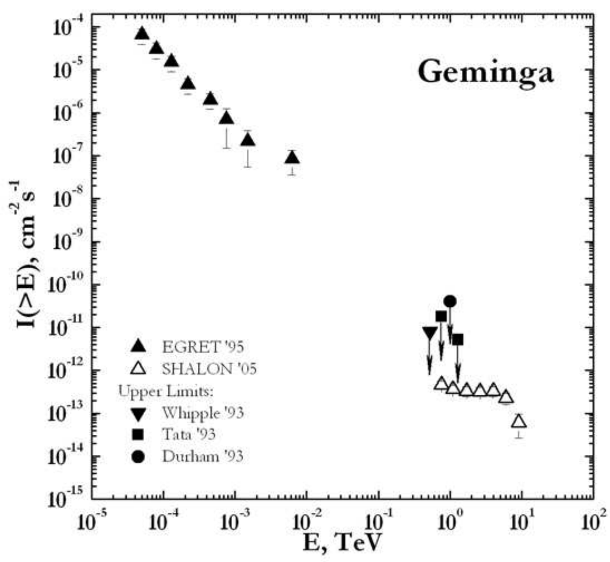

Fig. 6. The Geminga gamma - quantum ($E > 0.8$ TeV) integral spectrum by SHALON in comparison with other experiments

from Crab Nebula by SHALON telescope is shown in Fig. 3. The spectrum indices for Crab Nebula obtained by Whipple, SHALON, CANGAROO, CAT, HEGRA atmospheric Cherenkov telescopes and Tibet are presented in table II [5].

III. Geminga

Geminga is one of the brightest source of MeV - GeV gamma-ray, but the only known pulsar that is radio-quiet. Geminga has been the object for study at TeV energies with upper limits being reported by three experiments Whipple'93, Tata'93 and Durham'93. Figures 4, 5 and 6 show the SHALON results for this gamma-source. An image of gamma-ray emission from Geminga by SHALON telescope is shown in Fig. 5. As is seen from fig.6 the value Geminga flux obtained by SHALON is lower than the upper limits published before. Its integral gamma-ray flux is found to be $(0.48 \pm 0.17) \times 10^{-12}$ at energies of > 0.8 TeV. Within the range 0.8 - 5 TeV, the integral energy spectrum is well described by the single power law $I(> E_\gamma) \propto E_\gamma^{-0.58\pm0.11}$(Fig. 4). The energy spectrum of supernova remnant Geminga $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum.

IV. Tycho's SNR

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.

Tycho's SNR has been detected by SHALON at TeV energies. The integral gamma-ray flux above 0.8 TeV was

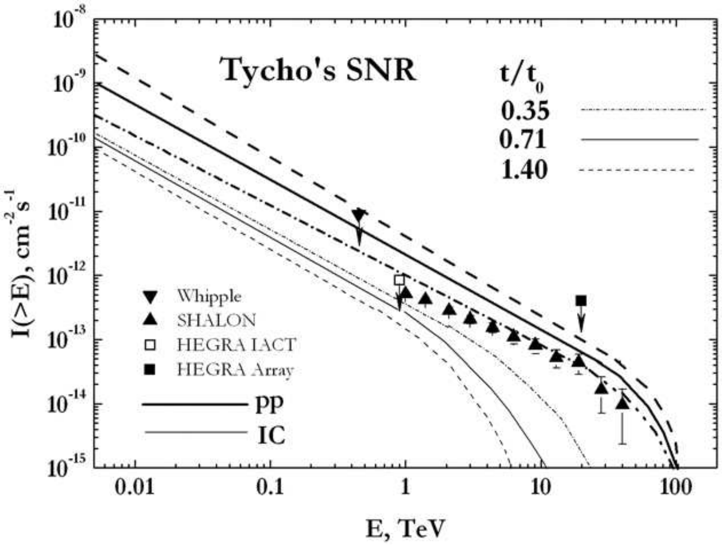

Fig. 7. The Tychos SNR gamma-quantum integral spectrum by SHALON in comparison with other experiments: the observed upper limits Whipple, HEGRA IACT system, HEGRA AIROBICC and calculations: IC emission (thin lines), π° - decay (thik lines).

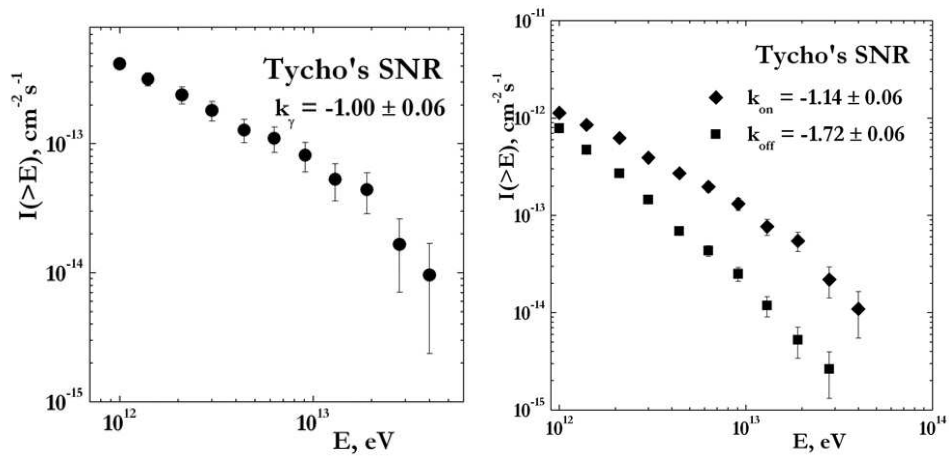

Fig. 8. left – The Tycho's SNR gamma-quantum integral spectrum with power index of $k_{\gamma} = -1.00 \pm 0.06$; right – the event spectrum from Tycho' SNR with background with index of $k_{ON} = -1.14 \pm 0.06$ and spectrum of background events observed simultaneously with Tycho's SNR with index $k_{OFF} = -1.72 \pm 0.06$.

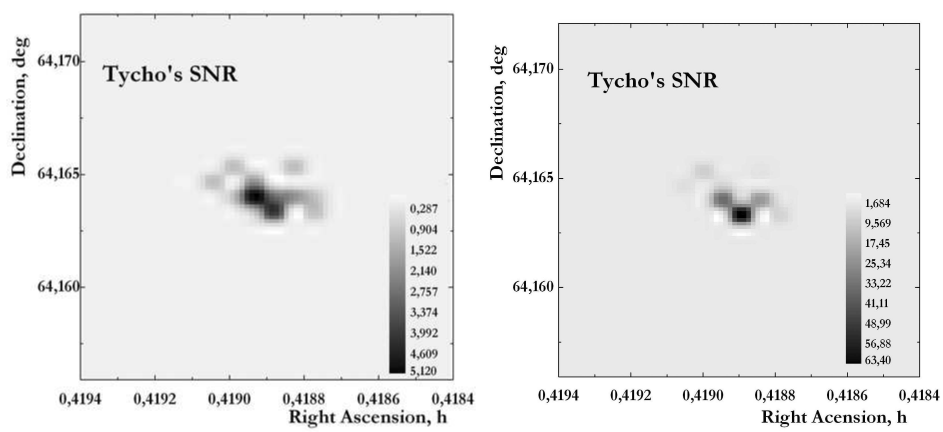

Fig. 9. left – The image of gamma-ray emission from Tycho's SNR; right – The energy image (TeV units) of Tycho's SNR by SHALON

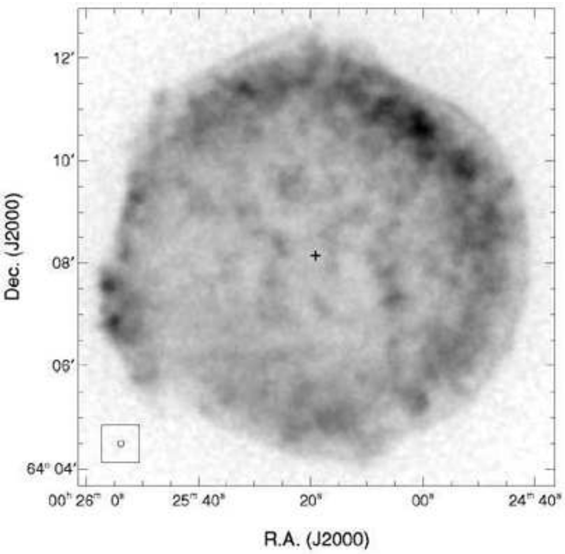

Fig. 10. ROSAT HRI image of Tycho's SNR

estimated as $(0.52\pm0.09)\times10^{-12}$ (Table I, Fig. 7). Figures 7, 8 show the observational results for the Tycho's SNR. An image of gamma-ray emission from Tycho's SNR by SHALON telescope is shown in Fig. 9. It coincides with spot of the maximum intensity in north-east part of rim viewed in X-ray by ROSAT, Fig. 10. The energy spectrum of Tycho's SNR at $0.8-20$ TeV can be approximated by the power law $F(>E_O) \propto E^{k_\gamma}$, with $k_\gamma = -1.00\pm0.06$. The integral spectral indices of k_{ON} and k_{OFF} are shown in Table III and Figures 8. The energy spectrum of supernova remnant Tycho's SNR $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum. A nonlinear kinetic model of cosmic ray acceleration in supernova remnants is used in [6], (Fig. 7), to describe the properties of Tycho's SNR. The kinetic nonlinear model for cosmic ray acceleration in SNR has 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 established a very low upper limit at energies >1 TeV. This value is consistent with that previously published by Whipple collaboration, being a factor of 4 lower (the spectral index of -1.1 for this comparison [6]). The π^O-decay gamma-quantum flux turns out to be some greater than inverse Compton flux at 1 TeV becomes strongly dominating at 10 TeV. The predicted gamma-quanta flux is in consistent with upper limits published by Whipple [8, 9] and HEGRA [7].

V. Conclusion

Since the expected flux of gamma-quanta from π^O-decay, $F_\gamma \propto E_\gamma^{-1}$, extends up to ~ 30 TeV, while the flux of gamma-rays originated from the Inverse Compton scattering has a sharp cutoff above the few TeV we may conclude that the detection of gamma-rays with energies of ~ 10 to 40 TeV by SHALON is an indication of their hadronic origin [6].

TABLE III

The integral spectrum indices of SHALON spectra in SNR

Sources	k_γ	k_{ON}	k_{OFF}
Tycho's SNR	-1.00 ± 0.06	-1.14 ± 0.06	-1.72 ± 0.06
Geminga	-0.58 ± 0.11	-0.85 ± 0.09	-1.72 ± 0.09
Crab Nebula	-1.44 ± 0.07	-1.60 ± 0.06	-1.74 ± 0.06

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