TeV gamma-rays from Galactic sources: Tycho's SNR, Geminga and Crab Nebula

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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 in northern hemisphere, 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 $F(E_O > 0.8\ TeV) \propto E^k$ are found to be harder than Crab Nebula spectrum. The integral energy spectrum of Crab Nebula is well described by the single power law $I(> E_\gamma) \propto E_\gamma^{-1.44\pm0.07}$. Geminga is one of the brightest sources of MeV - GeV gamma-ray. 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 $I(> E - \gamma) \propto E_\gamma^{-0.58\pm0.11}$. The integral gamma-ray flux of Tycho.s SNR above 0.8 TeV by SHALON was estimated as $(0.52 \pm 0.09) \times 10^{-12}$. The energy spectrum of Tycho's SNR at 0.8 - 20 TeV can be approximated by the power law $I(> E_\gamma) \propto E^{k_\gamma}$, with $k_\gamma = -1.00 \pm 0.06$. The expected π°-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 10 - 40 TeV by SHALON is the evidence of hadron origin.

Introduction

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 (supernova remnant), Cygnus X-3 (binary), Tycho's SNR (supernova remnant), Geminga (radioweak pulsar) and 2129+47 (binary) [1 - 14]. 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 Figs. 1, 2, 3, 4, 5, 6, the observation results of Galaxy gamma-sources are showed.

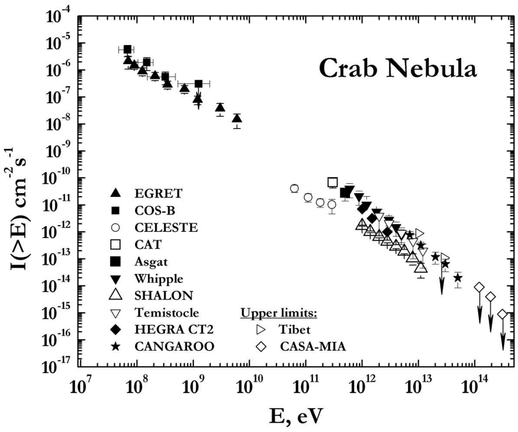

Figure 1: The Crab Nebula gamma-quantum integral spectrum by SHALON in comparison with other experiments: EGRET, COS-B, CELESTE, CAT, Asgat, Whipple, Themistocle, HEGRA CT2, CANGAROO, Tibet, CASA-MIA [1 - 5; 10 - 12].

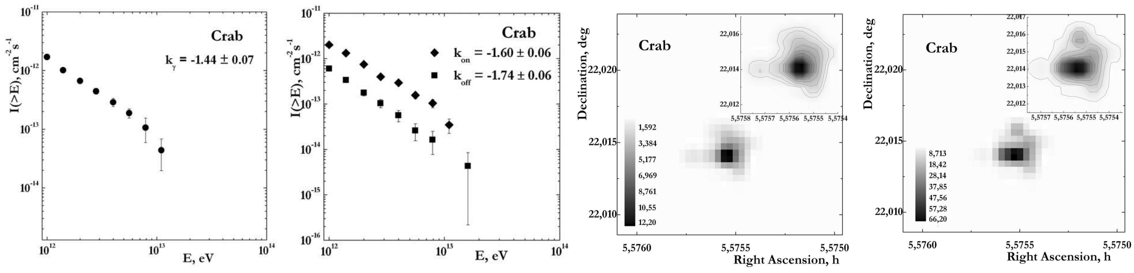

Figure 2: **left:** The Crab Nebula gamma-quantum integral spectrum with power index of $k_\gamma = -1.44 \pm 0.07$; The event spectrum from Crab Nebula with background with index of $k_{ON} = -1.60 \pm 0.06$ and spectrum of background events observed simultaneously with Crab Nebula with index $k_{OFF} = -1.74 \pm 0.06$. **right:** The image of gamma-ray emission from Crab; The energy image (TeV units) of Crab by SHALON.

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 presented below 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 $I(> E_\gamma) \propto E_\gamma^{-1.44 \pm 0.07}$(Fig. 2).

An image of gamma-ray emission from Crab Nebula by SHALON telescope is shown in Fig. 2. The spectrum indices for Crab Nebula obtained by Whipple, SHALON, CANGAROO, CAT, HEGRA atmospheric Cherenkov telescopes and Tibet are presented in [4, 5].

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 3 and 4 show the SHALON results for this gamma-source. An image of gamma-ray emission from Geminga by SHALON telescope is shown in Fig. 4. As is seen from fig.3 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 $I(> E_\gamma) \propto E_\gamma^{-0.58 \pm 0.11}$(Fig. 4). The

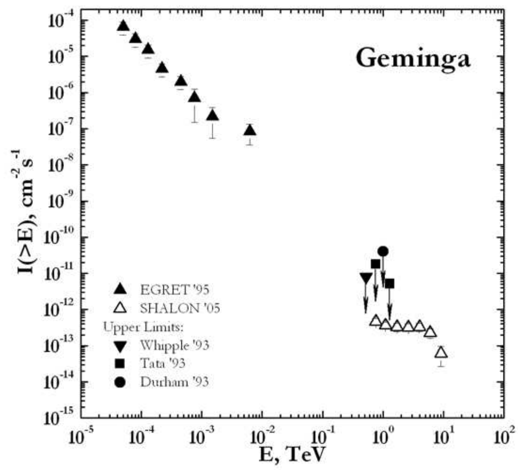

Figure 3: The Geminga gamma - quantum ($E > 0.8$ TeV) integral spectrum by SHALON in comparison with other experiments

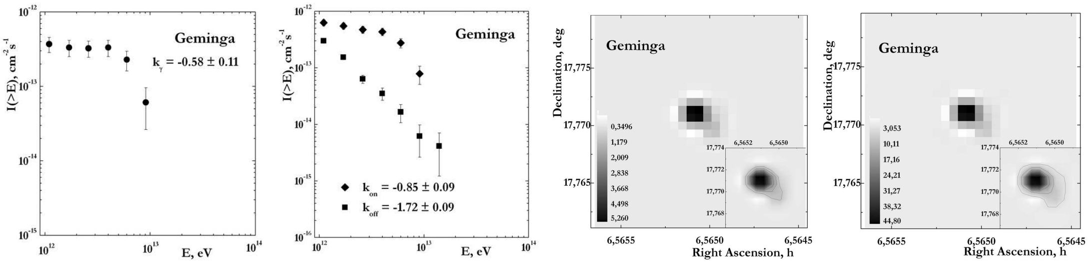

Figure 4: **left:** The Geminga gamma-quantum integral spectrum with power index of $k_\gamma = -0.58 \pm 0.11$; The event spectrum from Geminga with background with index of $k_{ON} = -0.85 \pm 0.09$ and spectrum of background events observed simultaneously with Geminga with index $k_{OFF} = -1.72 \pm 0.09$; **right:** The image of gamma-ray emission from Geminga; The energy image (TeV units) of Geminga by SHALON

energy spectrum of supernova remnant Geminga $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum.

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 estimated as $(0.52 \pm 0.09) \times 10^{-12}$ (Fig. 5). Figures 5, 6 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. 6. It coincides with spot of the maximum intensity in north-east part of rim viewed in X-ray by ROSAT [14]. 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 $k_\gamma = -1.00 \pm 0.06$. The integral spectral indices of k_{ON} and k_{OFF} are shown in Figures 6. 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. 5), 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].

Conclusion

Since the expected flux of gamma-quanta from π^O-decay, $F_\gamma \propto E_\gamma^{-1}$, extends up to $\sim$ 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 $\sim$ 10 to 40 TeV by SHALON is an indication of their hadronic origin [6].

References

[1] V. G. Sinitsyna, AIP Conf. Proc., 515, (1999) 205 and 293.

[2] V. G. Sinitsyna, S. I. Nikolsky, et al.,Izv. Ross. Akad. Nauk Ser. Fiz., 66(11),(2002) 1667 and 1660.

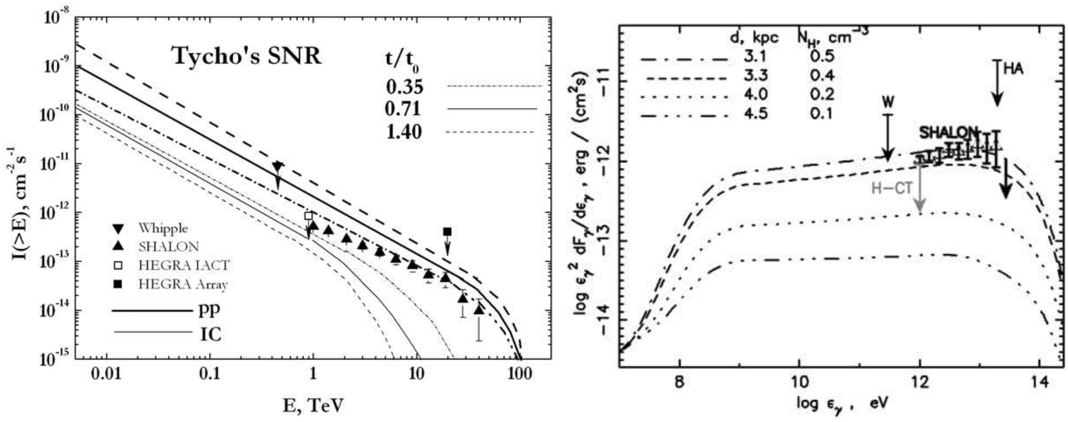

Figure 5: **left:** The Tycho's SNR gamma-quantum integral spectrum by SHALON in comparison with other experiments: the observed upper limits Whipple, HEGRA IACT system, HEGRA AIROBICC and calculations: IC emission (thin lines), π° - decay (thick lines). **right:** L. T. Ksenofontov, H.J. Vöek, E.G. Berezhko in The Multi-Messenger Approach to High Energy Gamma-ray Sources, Barcelona, July 4-7, 2006

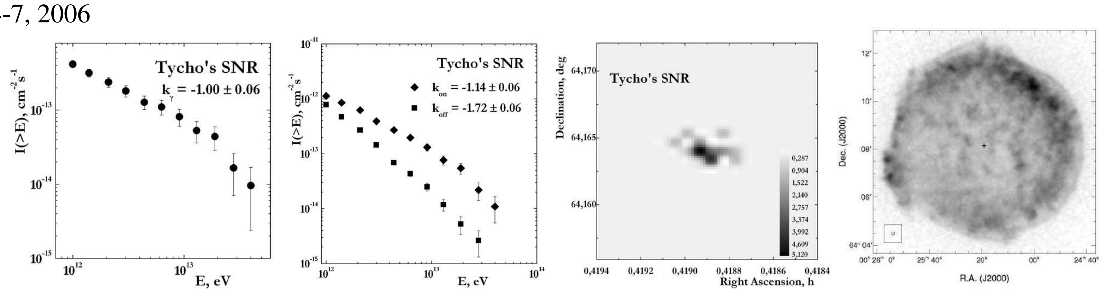

Figure 6: **left:** The Tycho's SNR gamma-quantum integral spectrum with power index of $k_\gamma = -1.00 \pm 0.06$; The event spectrum from Tycho' SNR with background with index of $k_{ON} = -1.14 \pm 0.06$ and spectrum of background events observed simultaneously with Tycho's SNR with index $k_{OFF} = -1.72 \pm 0.06$. **right:** The SHALON image of gamma-ray emission from Tycho's SNR and ROSAT HRI [14] image of Tycho's SNR

[3] V. G. Sinitsyna, et al.,in Proc. 27th Int. Cosmic Ray Conf., Hamburg, 3, (2001) 2665; in Proc. 29th Int. Cosmic Ray Conf., Puna, 4, (2005) 231.

[4] V. G. Sinitsyna et al.,Nucl. Phys. B (Proc.Suppl.), 151, (2006), 112; V. G. Sinitsyna et al., *ibid.* 122,(2003) 247; S. I. Nikolsky and V. G. Sinitsyna, *ibid.*, 122, (2003) 409; V. G. Sinitsyna et al., *ibid.*, 97,(2001) 215 and 219.

[5] T. C. Weekes, AIP Conf. Proc., 515, (1999) 3.

[6] H. J. Völk, E. G. Berezhko, et al., in Proc. 27th Int. Cosmic Ray Conf., Hamburg, 2, (2001) 2469.

[7] J. H. Buckley, C. W. Akerlof, D. A. Carter-Lwis, et al., Astron. Astrophys., 329, (1998) 639.

[8] M. Catanese and T. C. Weekes, Preprint Series, no. 4811, (1999).

[9] J. Prahl and C. Prosch (for the HEGRA Collaboration), in Proc. 25th Int. Cosmic Ray Conf., Durban, 3, (1997) 217.

[10] A. M. Hillas, et al., ApJ, 503, (1998) 744.

[11] T. Tanimori, et al., ApJ, 492, (1998) 133.

[12] F. Piron, et al., in Proc. 28th Int. Cosmic Ray Conf., Tsukuba, (2003) 2607.

[13] H. J. Völk, E. G. Berezhko and L. T. Ksenofontov, in Proc. 29th Int. Cosmic Ray Conf., Pune, 3, (2005) 235.

[14] J. P. Hughes, ApJ, 545, (2000) L53 - L56.