VHE spectral energy distributions of Crab Nebula compared with the prediction of Synchrotron Self-Compton emission model

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***Abstract*— 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. Crab Nebula has an extraordinary broad spectrum, attributed to synchrotron radiation of electrons with energies from GeV to PeV. This continuous spectrum appears to terminate near 10^8 eV and photons, produced by relativistic electrons and positrons ($\sim 10^{15}$ eV) via Inverse Compton, form a new component of spectrum in GeV - TeV energy range. 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. The SHALON observation results of well-known gamma-source Crab Nebula 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 $I(>E_\gamma) \propto E_\gamma^{-1.44\pm0.07}$. An image of gamma-ray emission from Crab Nebula by SHALON telescope is presented. The VHE spectral energy distribution of the Crab Nebula is compared with the predictions of a synchrotron self-Compton emission model in energy range 0.8 TeV to 11 TeV (Hillas et al. 1998).**

I. INTRODUCTION

The observations on Tien-Shan high-mountain station with SHALON Atmospheric Cherenkov Telescopic System had been carried out since 1992 year [1], [2], [3], [4]. The mirror telescopic system of SHALON consists of a composed mirror with the area of $11.2m^2$. It is equipped with a 144-photomultipher light-receiver that has the field of view $> 8°$ (the largest in the world. It enables one to continuously control the background of cosmic-ray particle emission and the atmosphere transparency, thus increasing the observation efficiency. During the period since 1992 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], [2], [3], [4], [5], [6], [7]. 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, and table II, the observation results of Galaxy gamma-sources are showed.

TABLE I
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 ± 0.7) $\times(E/TeV)^{-2.49\pm0.06_{stat}\pm0.04_{syst}}$	0.3
SHALON (2005)	$(1.7 \pm 0.12) \times 10^{-1}$ $\times(E/TeV)^{-2.44\pm0.07}$	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
Magic (2005)	$(1.5 \pm 0.18) \times 10^{-3}$ $\times(E/GeV)^{-2.58\pm0.16}$	0.3
HESS (2005)	$(2.86 \pm 0.06 \pm 0.57)$ $\times(E/TeV)^{-2.67\pm0.01_{stat}\pm0.1_{syst}}$ (3.76 ± 0.07) $\times(E/TeV)^{-2.39\pm0.03\times exp(E/(14.3\pm2.1))}$	0.44
Tibet HD (1999)	(4.61 ± 0.1) $\times10^{-1} \times (E/3,TeV)^{-2.62\pm0.17}$	3.0

II. CRAB NEBULA

Pulsar Wind Nebulae (PWN) is the class of objects considered as a particle accelerator in the Galaxy. One of the

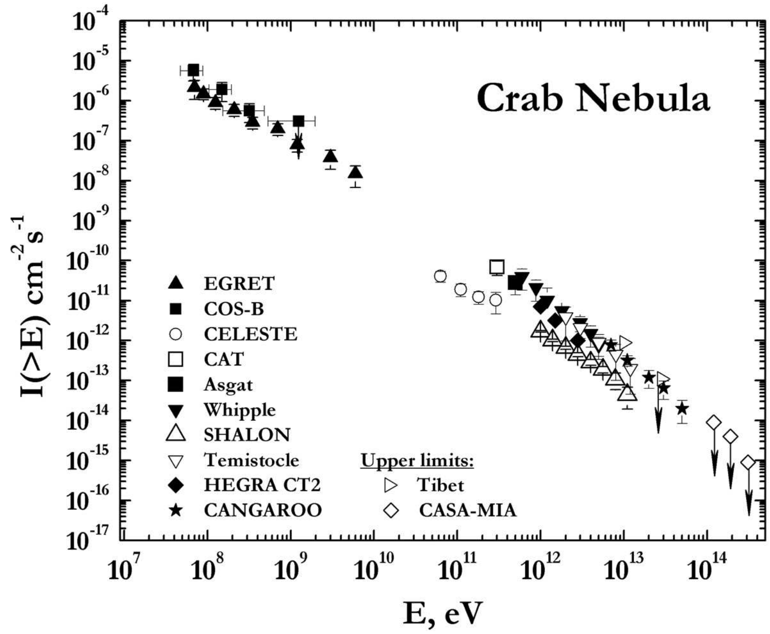

Fig. 1. The Crab Nebula gamma-quantum integral spectrum by SHALON in comparison with other experiments: EGRET, COS-B, CELESTE, CAT, Asgat, Whipple, Themistocle, HEGRA CT2, CANGAROO, Tibet, CASA-MIA [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13]

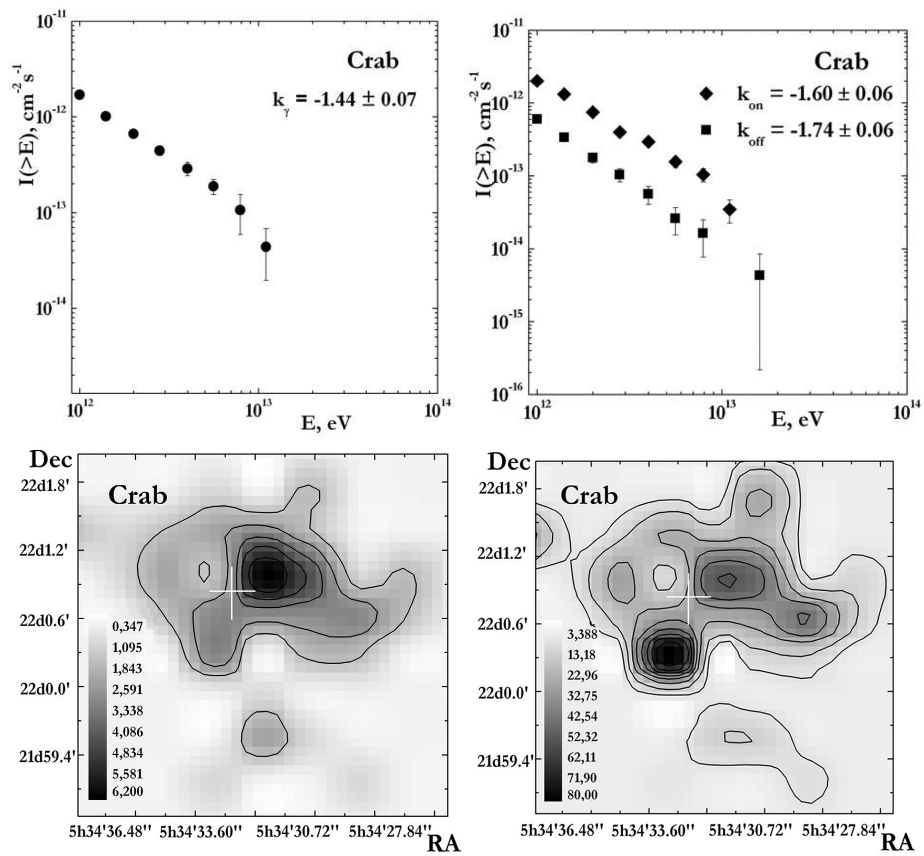

Fig. 2. **Top. left** – The Crab Nebula gamma-quantum integral spectrum with power index of $k_\gamma = -1.44 \pm 0.07$; **right** – The event spectrum from Crab Nebula with background with index of $k_{ON} = -1.60 \pm 0.06$ and spectrum of background events observed simultaneously with Crab Nebula with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

TABLE II

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

Sources	Source type	Observable flux ($cm^{-2}s^{-1}$)	Distance (kpc)
Crab Nebula (SNR)	Pulsar Wind Nebula	$(1.70 \pm 0.13) \times 10^{-12}$	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	Shell type SNR	$(0.52 \pm 0.09) \times 10^{-12}$	2.3
2129+47XR	Low-mass X-ray binary	$(0.19 \pm 0.09) \times 10^{-12}$	6

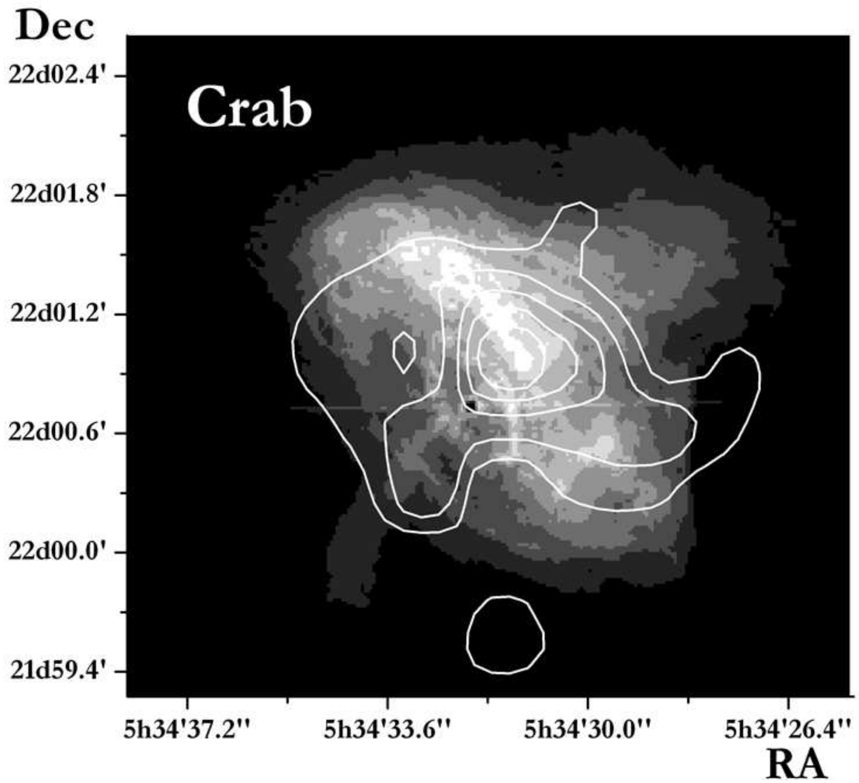

Fig. 3. A Chandra X-ray image of Crab Nebula. The central part 200" × 200" of Crab Pulsar Wind Nebula (PWN) in the energy range 0.2-20 keV. The white contour lines show the TeV - structure by SHALON observations.

PWN is Crab Nebula (very probably of Type II), observed through all bands of electromagnetic spectrum. As in many other bands of electromagnetic spectrum, the Crab Nebula has become the standard candle for TeV gamma-ray astronomy. It has been regularly observed by the number of independent groups using different methods of registration of gamma-initiated showers. 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 are presented at Figure 1 in comparison with other experiments EGRET, COS-B, CELESTE, CAT, Asgat, Whipple, Themistocle, HEGRA CT2, CANGAROO, Tibet, CASA-MIA. 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, table I). The spectrum indices for Crab Nebula obtained by Whipple, SHALON, CANGAROO, CAT, HEGRA atmospheric Cherenkov telescopes, Magic, HESS and Tibet are presented in table I and [4 – 16] Also, the results of observation data analysis are the images of Crab. A detailed image of gamma-ray emission from Crab Nebula by SHALON telescope is shown in Fig. 2.

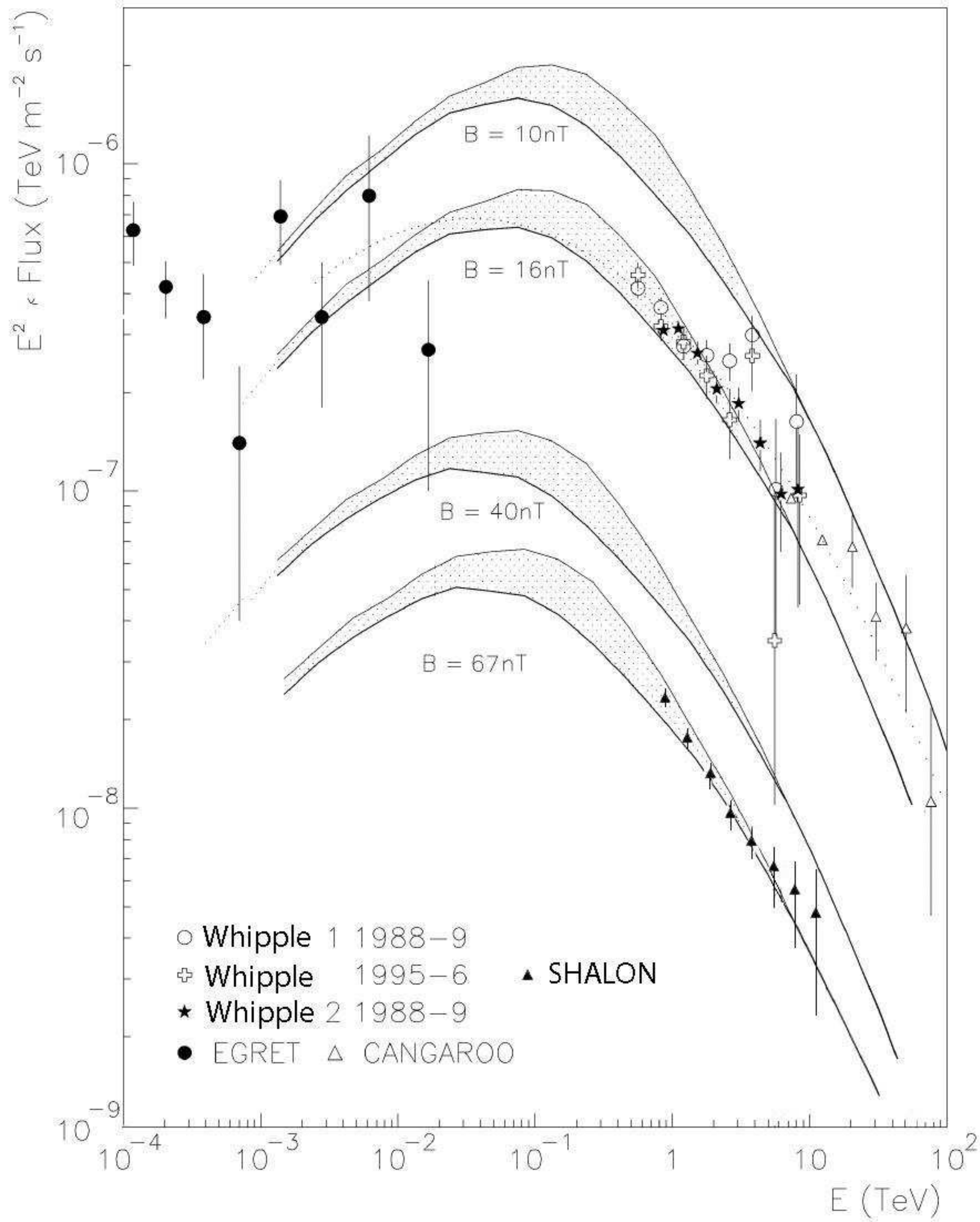

Fig. 4. The Crab Nebula gamma-quantum spectrum by SHALON together with other experiments: Whipple, EGRET, CANGAROO and with the predicted inverse Compton spectrum for the different field strengths [11] and for the 67 nT.

Crab Nebula has an extraordinary broad spectrum, attributed to synchrotron radiation of electrons with energies from GeV to PeV. This continuous spectrum appears to terminate near 10^8 eV and photons, produced by relativistic electrons and positrons ($\sim 10^{15}$ eV) via Inverse Compton, form a new component of spectrum in GeV TeV energy range.

For the purpose of calculating the Inverse Compton scattered radiation, the compleat spectrum of Crab Nebula need to be taken into account to deduce the spectrum of relativistic electrons (see ref. [11]). First, assuming magnetic field strength in the region of emission, shown in fig. 2, 3 and a distance of 2 kpc to the nebula, the number spectrum of electrons in the nebula can be deduced. Then the spectrum of emitted Inverse Compton scattered photons can be deduced from the electron spectrum [11].

In order to find relation between TeV and X-ray emission and characteristics which are necessary to calculate a VHE gamma-ray spectrum, the combination of SHALON and Chandra images were analyzed.

Figure 3 presents a Chandra X-ray image of the central part

TABLE III

MAGNETIC FIELDS AND LIFETIMES [17]

Region	Field (10^4 Gauss)	Lifetime (years)	Extent of region (light years)
PWN average	5.8	6.7	1.9 (60" radius)
bright Torus	7.7	4.3	1.7 (radius)
NW Loops	9.1	2.9	0.6
Jet center, region 7	9.1	2.9	1.8 (length of jet)
bright inner ring	10.8	2.6	0.08 (thickness of ring)
knot in bright inner ring	15.3	1.5	0.07 (size of knot)
S Finger, region 5	6.2	5.9	1.3 (length of finger)
SW Finger, region 7	6.2	5.9	1.6 (length of finger)

200" $\times$ 200" of Crab Nebula in the energy range 0.2-20 keV. In this energy band most of the PWN X-rays come from a torus surrounding the pulsar. The white contour lines show the TeV - structure by SHALON observations. The most part of TeV energy gamma-quanta come from the region of bright torus (see fig. 3, table III) whereas the contribution of energy gives the region of the southern jet (see fig. 2).

Magnetic fields and lifetimes of representative regions in Chandra image of Crab have been derived [17] and are listed in Table 3.

TeV gamma-quantum spectrum (see fig. 4) is generated by photons, produced by relativistic electrons and positrons via Inverse Compton if the average magnetic field in the region of VHE gamma-ray emission $\sim$ 67 nT (that is taken from the comparison of TeV and X-ray emission regions, see fig. 3 and table III). The observed by SHALON spectrum (see fig. 4) is close to the predicted flux of gamma rays due to Inverse Compton scattering of low energy photons by multi-TeV electrons in the Nebula, if the magnetic field of 67 nT in the region responsible for X-ray emission is taken into account.

III. CONCLUSION

The Inverse Compton emission that relativistic electrons would generate in the parts of Crab Nebula (see. Figures 2) is in good agreement with the TeV gamma-ray spectrum observed by SHALON, if the average magnetic field in the region of VHE gamma-ray emission is 67 nT which is taken from the comparison of TeV (SHALON data) and X-ray (Chandra data) emission regions.

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