TeV J2032+4130 - very high energy gamma-ray source of unresolved nature

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Abstract. The Cygnus Region is one of the brightest regions in all ranges of the electromagnetic spectrum and contains a number of potential GeV and TeV emission sources. It includes active star formation regions, pulsars and supernova remnants. Some of the sources have been detected at high and very high energies. One of them discovered due to its proximity to the well-known microquasar Cyg X-3 is the object TeV J2032+4130. This object is still of unresolved nature and is being intensively studied in different energy ranges. The results of twenty-year observations of TeV J2032+4130 by the SHALON experiment are presented in this paper. The collected experimental data on fluxes, spectrum shape and morphology of TeV J2032+413 can help in the future to determine an object type and reveal mechanisms of generation of very high energy emission.

1 Introduction

The Cygnus Region is one of the brightest areas of the sky in all wavelengths and is known to contain a number of potential GeV and TeV gamma-ray sources. Objects connected to this region include star association Cygnus OB2, the microquasar Cygnus X-3, supernova remnant Cygni SNR and the TeV J2032+4130 object. Some of the sources listed above have been detected at high energies with the Fermi LAT experiment [1–3] and earlier with the EGRET telescope [4, 5]. Also, it was detected at very high energies with the Milagro air shower array detector [6] and by imaging atmospheric Cherenkov telescopes Whipple [7], HEGRA [8], SHALON [9–11], VERITAS [12] and MAGIC [13].

TeV J2032+4130 was detected by the HEGRA telescopic system [8] at energies > 1 TeV during observations made in the years 1999 - 2001. This object was the first TeV gamma-ray detection having no bright counterpart at any other wavelength and was also the first extended source to be discovered in the very high energy range. Characteristics of TeV J2032+4130 in the energy range from 1 to 50 TeV were obtained with the SHALON telescope for the first time. The observation data on the TeV J2032+4130 object presented in this paper are the result of twenty-year-long investigations of the Cygnus Region by the SHALON experiment.

2 TeV J2032+4130

In accordance with the program on long-term studies of the microquasar Cygnus X-3 [9–11] at very high energies, observations of the Cygnus Region and its member objects, including TeV J2032+4130 are being carried out

with the high-mountain SHALON imaging atmospheric Cherenkov telescopes. TeV J2032+4130 is located at a distance of $\sim 0.5°$ north from Cyg X-3. So due to the large telescopic field of view $> 8°$ the observations of Cygnus-X are naturally followed by tracking TeV J2032+4130.

As a result, TeV J2032+4130 as a source accompanying Cyg X-3 has been systematically observed with the SHALON telescope (since 1995 up to now) during clear moonless nights at zenith angles from $5°$ to $34°$. The observations were performed using the standard SHALON technique of recording information about the cosmic-ray background and gamma-ray-initiated showers in the same observing session [14–16]. With the data processing, TeV J2032+4130 was detected above 0.8 TeV by SHALON with a statistical significance 31σ determined by the Li&Ma method [17]. The average integral flux at energies above 0.8 TeV for TeV J2032+4130 is $I_{TeV J2032+4130} = (0.84 \pm 0.05) \times 10^{-12}$ cm^{-2}s^{-1}. After processing the Cyg X-3 observation data, first by selection criteria associated with Cyg X-3 and then with TeV J2032+4130, we found that 8.1% of showers are common for both sources. Recognition of the source for each of the common showers is performed by analysing the angular distance of the arrival direction of these showers and the source coordinates. As a result, less than 4% of Cyg X-3 showers were recognized to be TeV J2032+4130 showers. This didn't change the average flux of Cyg X-3.

The differential γ-ray energy spectrum of TeV J2032+4130 in the energy range from 0.8 to 50 TeV obtained by SHALON telescope is presented in Fig. 1. In the energy range 0.8 - 15 TeV the differential spectrum of TeV J2032+4130 is well described by the power law $F(E > 0.8 \text{ TeV}) \propto E^k$, with $k = -1.73 \pm 0.10$ (see Fig. 1, top). Also, the source image in TeV-energies by SHALON are shown in Figure 1, bottom. Analysis of the γ-shower

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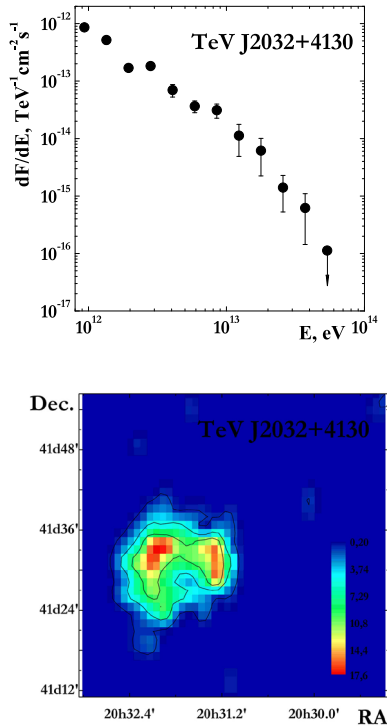*e-mail: sinits@sci.lebedev.ru

Figure 1. TeV J2032+4130 characteristics: **top** - differential gamma-ray spectrum in the energy range 1 - 50 TeV; **bottom** - The image of TeV J2032+4130 at energies > 0.8 TeV by SHALON

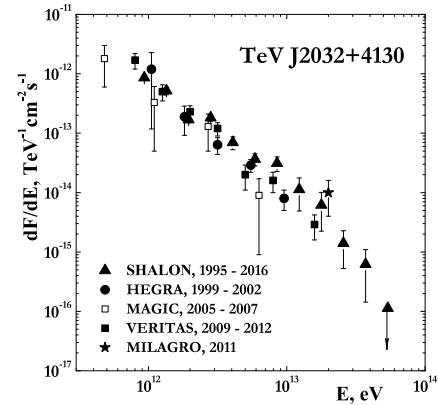**Figure 2.** Differential spectrum of TeV J2032+4130 by SHALON (▲) compared with HEGRA, VERITAS, MAGIC and MILAGRO experiments (see text).
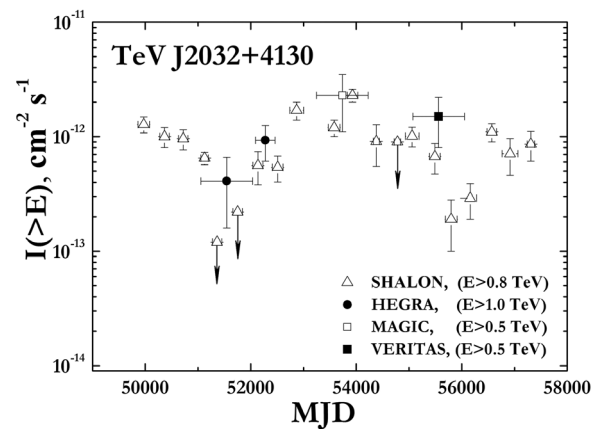

Figure 3. The light curve of TeV J2032+4130 at very high energies obtained in the long-term SHALON observations compared with HEGRA, MAGIC, and VERITAS experimental data.

direction showed that the emission source is an extended area of ~ 10′ size, coinciding with the experimental data of HEGRA [8], VERITAS [12] and MAGIC [13] (see the references, available from the references).

Very high energy data on the TeV J2032+4130 energy spectrum were obtained in different years with the HEGRA [8], VERITAS [12] and MAGIC [13] ground-based telescopes and with the MILAGRO [6] detector. Figure 2 shows the comparison of differential energy spectra of TeV J2032+4130 by SHALON (1995-2016), HEGRA(1999 - 2002), MAGIC (2005 - 2007), VERITAS (2009 - 2012) and data of MILAGRO (2011).

The differential spectrum was obtained with the VER-ITAS experiment in the energy region 700 GeV - 16 TeV. It is well fitted by a power law $dN/dE = C \times (E/1 TeV)^{-\Gamma}$ with a spectral index of $\Gamma = 2.1 \pm 0.14_{stat} \pm 0.21_{sys}$ and normalization at 1 TeV of $C = (9.5 \pm 1.6_{stat} \pm 2.2_{sys}) \times 10^{-13}$ TeV^{-1} cm^{-2}sec^{-1}. with the $\chi^2 = 0.9$ per degree of freedom is $4.5/5 = 0.9$.

The differential spectrum of TeV J2032+4130 obtained with MAGIC can be fitted by a power law function with the $\chi^2 = 0.9$ in the form of $dN/dE = (4.5 \pm 0.3) \times 10^{-13} \times (E/1 TeV)^{-2.0 \pm 0.3}$.

The spectrum of TeV J2032+4130 in the energy range 1 - 10 TeV was measured in HEGRA observations in the period 1999 - 2000. The shape is consistent with a power law $dN/dE = C \times (E/1 TeV)^{-\Gamma}$ with the following parameters $C = (6.2 \pm 1.5_{stat} \pm 1.3_{sys}) \times 10^{-13}$ cm^{-2}sec^{-1} and $\Gamma = 1.9 \pm 0.1_{stat} \pm 0.3_{sys}$.

The shape of the SHALON differential spectrum of gamma rays from TeV J2032+4130 in the energy range from 0.8 to 35 TeV fits well to a hard power law with an exponential cutoff (see. Fig. 2, ▲): $dN/dE = (7.1 \pm 1.1) \times 10^{-13} \times (E_\gamma/1 TeV)^{-1.50 \pm 0.11} \times exp(-E_\gamma/(16 \pm 3)$ TeV$)$ with the $\chi^2/Dof = 1.31$ where degree of freedom $Dof = 8$.

The twenty-year-long SHALON observations of TeV J2032+4130 revealed flux variations at energies > 0.8 TeV. Figure 3 shows the light curve of TeV J2032+4130 obtained in the SHALON experiment over the entire period of observations from 1995 to 2015 in comparison with the HEGRA, MAGIC, and VERITAS data. The white triangles indicate the integral fluxes from the SHALON data averaged over each year of observation. The integral fluxes for TeV J2032+4130 from the data of other telescopes shown in Fig. 3 were determined in different time intervals: HEGRA (1999 – 2001, 2002), MAGIC (2005 – 2007) and VERITAS (2009 – 2012). The mean integral flux for TeV J2032+4130 at energies > 0.8 TeV from the SHALON data was $(1.01 \pm 0.15) \times 10^{-12}$ cm^{-2} s^{-1} in the observation periods 1995 - 1997, 2003 - 2006, and 2013 - 2015; $(0.58 \pm 0.12) \times 10^{-12}$ cm^{-2} s^{-1} in 1998, 2001, 2002, 2010, and 2016; and a low flux, $(0.12 \pm 0.09) \times$
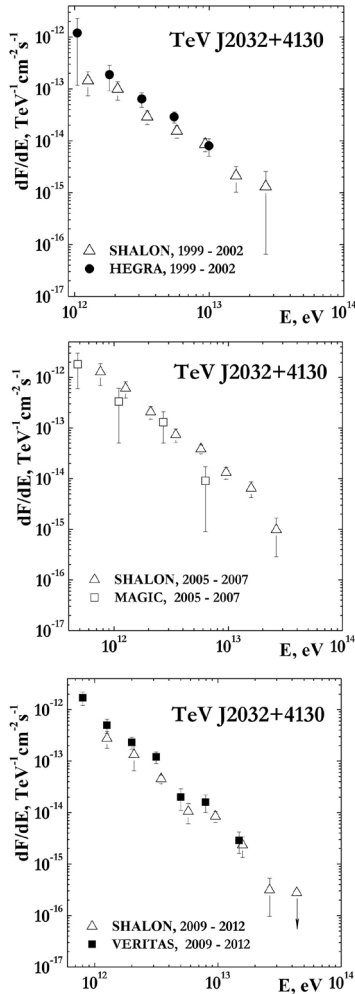
Figure 4. Differential spectra of TeV J2032+4130 averaged over different periods of its observations from the SHALON data compared with the HEGRA (1999 - 2002), MAGIC (2005 - 2007), and VERITAS (2009 - 2012) experimental data.

10^{-12} cm^{-2} s^{-1}, was recorded in 1999, 2000, 2011, and 2012.

The differential spectra of TeV J2032+4130 from the SHALON data averaged over the corresponding periods of its observations in the HEGRA (1999 - 2002), MAGIC (2005 - 2007) and VERITAS (2009 - 2012) experiments are compared in Fig. 4.

3 TeV J2032+413 nature

The nature of the extended object TeV J2032+413 still remains unresolved. Since the discovery of TeV J2032+4130 several observations of the region have been made by X-ray telescopes Chandra, XMM-Newton which operate in the energy range of 0.1 - 10 keV and 0.2 - 12 keV respectively. Multiple point sources were detected in the region of TeV J2032+413 by Chandra, XMM-Newton telescopes and then after the known point sources were subtracted XMM-Newton detected an extended X-ray emission region (see [12, 18]). Radio observations

of the region have been made using the GMRT, yielding at least three sources of non-thermal emission along with an extended non-thermal diffuse emission. Moreover, VLA observations revealed shell-like structure of weak radio emission [18] consistent with the dimensions of the TeV source reported by HEGRA, VERITAS, MAGIC and SHALON.

4 Conclusion

The results of long-term observations of the TeV J2032+4130 object by the imaging atmospheric Cherenkov telescope SHALON are presented. The collected experimental data and refining of fluxes, spectrum shape and morphology of TeV J2032+413 can help in the future to determine an object type and to shed light on the source nature.

References

[1] A.A. Abdo, B. Allen, D. Berley et al., Astrophys. J. **658**, L33 (2007)

[2] A.A. Abdo, M. Ackermann, M. Ajello et al., Science. **326**, 1512 (2009)

[3] A.A. Abdo, M. Ackermann, M. Ajello et al., Astrophys. J. **187**, 460 (2010)

[4] D.J. Thompson, D.L. Bertsch, B.L. Dingus et al., Astrophys. J. Suppl. Ser. **101**, 259 (1995)

[5] J.A. Esposito, S.D. Hunter, G. Kanbach and P. Sreekumar, Astrophys. J. **461**, 820 (1996)

[6] A.A. Abdo, B.T. Allen, T. Aune et al., Astrophys. J. **734**, 28 (2011)

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

[8] F. Aharonian, A. Akhperjanian, M. Beilicke et al., Astron. Astrophys. **431**, 197 (2005)

[9] V.G. Sinitsyna, in Proc. 16th European Cosmic Ray Symposium, ed. J. Medina, (Alcala de Henares: Universidad de Alcala, Spain), 383 (1998).

[10] V.G. Sinitsyna, V.Y. Sinitsyna, , Bulletin of the Lebedev Physics Institute, (New York: Allerton Press, Inc.), **40(5)**, 113 (2013).

[11] V.G. Sinitsyna and V.Y. Sinitsyna, EPJ Web of Conferences **145**, 04002 (2017)

[12] E. Aliu, T. Aune, B. Behera et al., Astrophys. J. **783**, 16 (2014)

[13] J. Albert, E. Aliu, H. Anderhub et al., Astrophys. J. **675**, L25 (2008)

[14] V.G. Sinitsyna Nuovo Cimento **19C(6)**, 965 (1996)

[15] V.G. Sinitsyna, V. Yu.. Sinitsyna, Astr. Lett. **40(2-3)**, 75 (2014)

[16] V.G. Sinitsyna et al., Adv. Space Res. doi:10.1016/j.asr.2017.04.007 (2017)

[17] T.-P. Li and Y.-Q. Ma, Astrophys. J. **272**, 317 (1983)

[18] Y.M. Butt, J.A. Combi, J. Drake et al., Mon. Not. Roy. Astron. Soc. 385, 1764 (2008)