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EVIDENCE FOR LONG-TERM GAMMA-RAY AND X-RAY VARIABILITY FROM THE UNIDENTIFIED TeV SOURCE HESS J0632+057

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ABSTRACT

HESS J0632+057 is one of only two unidentified very-high-energy gamma-ray sources which appear to be point-like within experimental resolution. It is possibly associated with the massive Be star MWC 148 and has been suggested to resemble known TeV binary systems like LS I +61 303 or LS 5039. HESS J0632+057 was observed by VERITAS for 31 hr in 2006, 2008, and 2009. During these observations, no significant signal in gamma rays with energies above 1 TeV was detected from the direction of HESS J0632+057. A flux upper limit corresponding to 1.1% of the flux of the Crab Nebula has been derived from the VERITAS data. The nondetection by VERITAS excludes with a probability of 99.993% that HESS J0632+057 is a steady gamma-ray emitter. Contemporaneous X-ray observations with the *Swift* X-Ray Telescope reveal a factor of 1.8 ± 0.4 higher flux in the 1–10 keV range than earlier X-ray observations of HESS J0632+057. The variability in the gamma-ray and X-ray fluxes supports interpretation of the object as a gamma-ray emitting binary.

Key words: acceleration of particles – binaries: general – gamma rays: observations – stars: individual (HESS J0632+057, MWC 148)

1. INTRODUCTION

HESS J0632+057 is one of about 20 very-high-energy (VHE) gamma-ray sources with no known counterparts at other wavelengths (for a recent review, see, e.g., Weekes 2008). Gamma-ray emission was discovered by the High Energy Stereoscopic System (HESS) during observations of the Monoceros Loop Supernova Remnant in 2004 and 2005 (Aharonian et al. 2007). It appears to be point-like within experimental resolution;

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the limit on the size of the emission region was given as $2'$ (95% confidence level). The reported flux of gamma rays with energies above 1 TeV from HESS J0632+057 corresponds to about 3% of the flux of the Crab Nebula, with a differential photon spectrum consistent with a power-law function with index of $2.53 \pm 0.26_{\text{stat}} \pm 0.20_{\text{sys}}$. Possible associations considered by Aharonian et al. (2007) are the Monoceros Loop Supernova remnant, the weak X-ray source 1RXS J063258.3+054857, the B0pe-star MWC 148 (HD 259440), and the unidentified GeV gamma-ray source 3EG J0634+0521 (Hartman et al. 1999). Follow-up X-ray observations with *XMM-Newton* by Hinton et al. (2009) revealed a variable X-ray source (XMMU J063259.3+054801) with a position compatible with HESS J0632+057 and MWC 148. It should be noted that 3EG J0634+0521 is absent in the EGR catalogue of EGRET gamma-ray sources, a reanalysis of the EGRET data with new Galactic interstellar emission models and interstellar radiation field data (Casandjian & Grenier 2008). 3EG J0634+0521 is, as expected from the reported flux, not in the Fermi bright gamma-ray source list (Abdo et al. 2009).

Point-like gamma-ray sources stand out among the many galactic VHE objects with spatially extended gamma-ray emission. The latter are usually associated with either pulsar wind nebulae or supernova remnants. High-mass X-ray binaries constitute the only known class of galactic objects with variable point-like VHE emission; this class currently contains three members only: PSR B1959-63/SS 2883 (Aharonian et al. 2005b), LS 5039 (Aharonian et al. 2005c), and LS I +61 303 (Albert et al. 2006; Acciari et al. 2008). Additionally, marginal evidence at a level of 3.2σ from the black-hole binary Cyg X-1 has been reported by Albert et al. (2007). TeV binaries show variable emission of gamma rays, likely connected to changes in physical parameters associated with the orbital movement. VHE gamma-ray production in these objects is explained by the acceleration of charged particles in accretion-powered relativistic jets (Taylor & Gregory 1984; Mirabel & Rodriguez 1994) or in shocks created by the collision of the expanding pulsar wind with the wind from the stellar companion (Maraschi & Treves 1981). Subsequent inverse-Compton scattering on low-energy stellar photons produces gamma rays at GeV and TeV energies. While there has been no compact companion discovered for MWC 148, the point-like nature of the VHE emission combined with the variable X-ray emission can easily be explained by a production scenario similar to those in TeV binaries. A second possible scenario is that MWC 148 is a representative of a new type of VHE emitter as proposed by Babel & Montmerle (1997) and Townsend et al. (2007). In their picture strong magnetic fields around the massive star lead to magnetically channeled wind shocks in which second-order Fermi acceleration might occur. However, it is not clear if the circumstellar environment of MWC 148 is strongly magnetized, or if this acceleration mechanism is able to produce particles of sufficiently high energy to produce a measurable TeV flux. An association of HESS J0632+057 with the Monoceros loop SNR is unlikely given the point-like nature of the gamma-ray emission and the non-correlation of possible target material with the position of the VHE source (Aharonian et al. 2007).

2. OBSERVATIONS

VERITAS is an array of four imaging atmospheric-Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona. It combines a large effective area (up to 10^5 m^2) over a wide energy range (100 GeV to 30 TeV) with good energy (15%–20%) and angular ($\approx 0.^\circ1$) resolution. The field of view of the VERITAS telescopes is $3.^\circ5$. The high sensitivity of VERITAS enables the detection of sources with a flux of 1% of the Crab Nebula in less than 50 hr of observations. For more details on the VERITAS instrument, see, e.g., Acciari et al. (2008).

VERITAS observed the sky around HESS J0632+057 during three periods in 2006 December, 2008 December, and 2009 January; see Table 1 for details. For each period, data equivalent to 10 hr of observations passed quality selection criteria, which remove data taken during bad weather or with hardware-related problems. Data were taken on moonless nights in wobble mode, wherein the source was positioned $0.^\circ5$ from the camera center with the offsets in different positions for different runs. The first data set (Set I) consists of observations taken during the construction phase of VERITAS with only three telescopes. These observations were pointed toward the center of the Monoceros region (at an angular distance of $\sim 0.^\circ5$ from HESS J0632+057), while observations in the second and third sets were targeted around the reported position of HESS J0632+057.

The data analysis steps consist of image calibration and cleaning, second-moment parameterization of these images (Hillas 1985), stereoscopic reconstruction of the event impact position and direction, gamma-hadron separation, spectral energy reconstruction (see, e.g., Krawczynski et al. 2006), as well as the generation of photon sky maps. The majority of the far more numerous background events are rejected by comparing the shape of the event images in each telescope with the expected shapes of gamma-ray showers modeled by Monte Carlo simulations. These *mean-reduced-scaled width* and *mean-reduced-scaled length* cuts (see definition in Krawczynski et al. 2006), and an additional cut on the arrival direction of the incoming gamma ray (Θ^2) reject more than 99.9% of the cosmic-ray background while keeping 45% of the gamma rays. The cuts applied here are: integrated charge per image > 1200 digital counts ($\approx$ 225 photoelectrons), $-1.2 <$ mean-reduced-scaled width/length < 0.5, and $\Theta^2 < 0.015$ deg^2 ($\Theta^2 < 0.025$ deg^2 for the three-telescope data set). The background in the source region is estimated from the same field of view using the "reflected-region" model with 8–10 background regions (Aharonian et al. 2001) and the "ring-background" model with a ring size of $0.^\circ5$ (mean radius) and a ring width of $0.^\circ175$ (Aharonian et al. 2005a). This analysis has been chosen to provide best sensitivity at high energies, in order to compare more directly with the results reported in Aharonian et al. (2007). The resulting energy threshold is 720 GeV.

Observations of XMMU J063259.3+054801 (HESS J0632+057) were taken with the *Swift* satellite over four consecutive nights, from 2009 January 26 to January 29, and were contemporaneous with VERITAS observations (Set III). The analysis is restricted to X-ray data from the X-Ray Telescope (XRT) instrument (Burrows et al. 2005) since the source is not detected with the Burst Alert Telescope (BAT) and the bright star MWC 148 causes a very high level of photon-coincidence losses in the UVOT instrument (Poole et al. 2008).[30] The presented *Swift*/XRT observations were conducted in photon-counting (PC) mode with no signatures of pile-up. Data reduction is performed with the HEAsoft 6.5 package. Events with grades 0–12 in the energy range of 0.3–10 keV are calibrated and cleaned using the *xrtpipeline* tool by applying the standard filtering criteria and latest *Swift* calibration files. Source counts

[30] It should be noted that MWC 148 with a B magnitude of less than 9 is too faint to introduce systematic effects into the analysis of the VERITAS data.

Table 1
Details of the VERITAS and HESS (Aharonian et al. 2007) Observations of HESS J0632+057

Name	Date Range	N_{Tel}[a]	Elevation Range	Angular Distance Between Source and Pointing Direction	Observation Time (minutes)
Set I	2006 Dec 16–2007 Jan 25	3	55°–65°	0°.15–0°.8	580
Set II	2008 Dec 30–2009 Jan 3	4	59°–65°	0°.5	560
Set III	2009 Jan 26–2009 Jan 30	3/4	59°–65°	0°.5	722
HESS P1	2004 Dec				282
HESS P2	2005 Nov–2005 Dec				372

Notes. [a] Number of available telescopes.

Table 2
Analysis Results for HESS J0632+057 for $E > 1$ TeV

Name	*On* Events	*Off* Events	α	Excess Events	Significance (σ)	Flux or Upper Flux Limit (10^{-13} cm^{-2} s^{-1})
Set I	84	594	0.16	−8.8	−0.9	< 4.2
Set II	131	713	0.16	15.7	1.3	< 4.2
Set III	120	669	0.16	11.4	1.0	< 3.6
Total (I-III)	335	1976	0.16	19.4	1.0	< 2.6
HESS P1						6.3 ± 1.8
HESS P2						6.4 ± 1.5

Notes. Upper limits $\Phi_{\gamma,\mathrm{UL}}(E > 1\ \mathrm{TeV})$ are given at 99% confidence level (after Helene 1983). The integral fluxes and 1 σ errors above 1 TeV reported by the HESS are listed for comparison (Aharonian et al. 2007).

are extracted from a circular region with a 30-pixel radius (47.2 arcsec), and background events are extracted from a 40 pixel radius circle in a source-free region. Ancillary response files are generated with the *xrtmkarf* tool applying corrections for the PSF losses and CCD defects. The latest response matrix from the XRT calibration files are used in the analysis. To ensure valid χ^2 minimization statistics during spectral fitting, the extracted XRT energy spectra are rebinned to contain a minimum of 25 counts in each bin.

3. RESULTS

Results for each of the three VERITAS data sets (see Table 1), as well as for the total observation, are listed in Table 2. Figure 1 shows a sky map of the significance at energies above 720 GeV observed in the region around HESS J0632+057. The distribution of significances in the sky map is consistent with the expected distribution from a field with no gamma-ray source present. The significance at the position of HESS J0632+057 is 2.1σ (1σ for an energy threshold of 1 TeV; see Table 2). Therefore no significant evidence for gamma-ray like events from HESS J0632+057 has been observed during the 31 hr of observations with VERITAS. The flux upper limit ($E > 1$ TeV) for the complete data set at the 99% confidence level (Helene 1983) assuming a power-law-like source spectrum with a spectral index of $\Gamma = 2.5$ is $F(> 1\ \mathrm{TeV}) < 2.6 \times 10^{-13}$ cm^{-2} s^{-1} (about 1.1% of the flux of the Crab Nebula; see Table 2). This flux limit is ~ 2.4 times lower than the flux reported by the HESS in Aharonian et al. (2007); see Figure 2 for a light curve. The probability for a non-variable flux of high-energy gamma rays from HESS J0632+057 is derived from the VERITAS data and the average of the reported fluxes from the HESS using a χ^2-test. The test gives a χ^2 of 15.8 with 1 degree of freedom, corresponding to a probability of 0.007% (about 4σ).

The nondetection of HESS J0632+057 by VERITAS initiated additional and very thorough quality checks of the data. Optical pointing monitors which are installed on each telescope show that the systematic error on the pointing was less than 90″ during the data-taking period for Set II and III.[31] The sensitivity of VERITAS in the elevation range of 50°–60° was confirmed by observations of the Crab Nebula and several other weak gamma-ray sources in early 2009 (e.g., Ong et al. 2009).

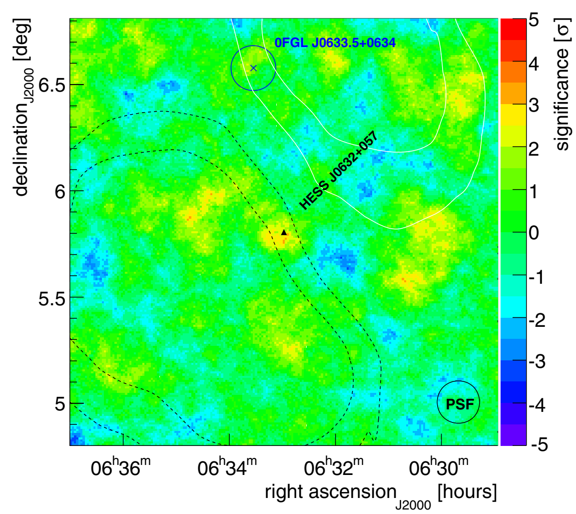

Figure 1. VERITAS significance map of the region around HESS J0632+057 for the whole data set and an energy threshold of 720 GeV. The background is estimated using the ring background method. The location of HESS J0632+057 is indicated by a black triangle. Also shown are the 95% and 99% confidence regions of the EGRET sources 3EGJ0634+0521 (white lines) and 3EGJ0631+0642 (GeV J0633+0645) (black lines). The Fermi source 0FGLJ0633.5+0634 is indicated with a "x" sign; the blue circle denotes the 95% confidence region (Abdo et al. 2009). The circle at the bottom right indicates the angular resolution of the VERITAS observations.

The *Swift* XRT observations provide further evidence for X-ray flux variability in the object. The total photon spectrum from the four *Swift* XRT observations in 2009 January is well described by an absorbed power law. Due to the low counting statistics, a fixed column density of $N_{\mathrm{H}} = 3.1 \times 10^{21}$ cm^{-2}

31 There were no pointing monitors installed in 2006 December (Set I).

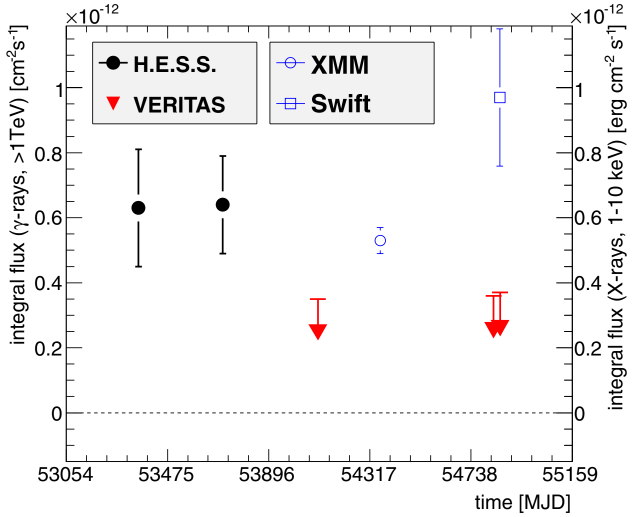

Figure 2. Light curve above 1 TeV from HESS J0632+057 is shown assuming a spectral shape of $dN/dE \propto E^{-\Gamma}$ with $\Gamma = 2.5$. The downward pointing arrows show the 99% confidence limits derived here from the VERITAS data. The HESS fluxes are taken from Aharonian et al. (2007). The X-ray fluxes measured by *XMM-Newton* and *Swift* are indicated by open symbols.

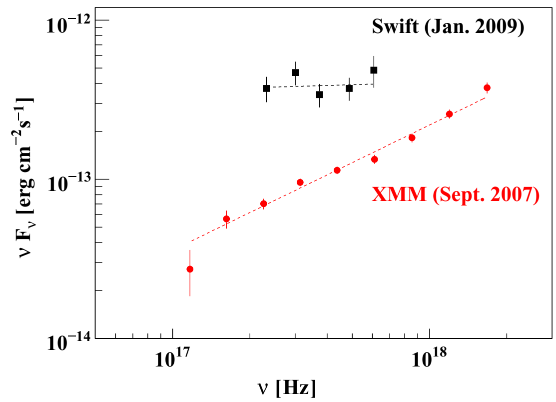

Figure 3. X-ray spectrum of HESS J0632+057 from *XMM-Newton* EPIC data in 2007 September (Hinton et al. 2009) and *Swift*/XRT observations in 2009 January.

is applied in the spectral analysis, as measured for the *XMM-Newton* EPIC spectrum (Hinton et al. 2009). The best-fit absorbed power-law model yields a $\chi^2/\mathrm{dof} = 3.5/7$, a photon index $\Gamma = 1.9 \pm 0.3$, and a 1 keV normalization of $(2.4 \pm 0.6) \times 10^{-4}$ cm^{-2} s^{-1} keV^{-1}. The deabsorbed 1–10 keV flux is $(9.7 \pm 2.1) \times 10^{-13}$ erg cm^{-2} s^{-1}, corresponding to a factor of 1.8 ± 0.4 higher flux than the *XMM-Newton* EPIC data. Among the four *Swift*/XRT observations no significant flux variability is measured. Figure 3 shows the deabsorbed X-ray spectra from the *Swift* and *XMM-Newton* observations. Over the limited energy range of 0.8–4 keV, the *Swift* photon spectra is softer ($\Gamma = 1.9 \pm 0.3$) than the *XMM-Newton* EPIC spectrum ($\Gamma = 1.26 \pm 0.04$). The relatively hard ($\Gamma \leqslant 2$) X-ray spectrum is similar to the spectral slopes measured from the TeV binaries LS I +61 303 (Leahy et al. 1997), LS 5039 (Hoffmann et al. 2009), and PSR B1259-63/SS 2883 (Chernyakova et al. 2006). No definite conclusion can be drawn from the X-ray spectral variability of HESS J0632+057. It appears, for example, from observations of PSR B1259-63/SS 2883 (Chernyakova et al. 2006) that the photon index of the X-ray spectra in TeV binaries is not a strictly monotonic function of flux. Detailed results from the full *Swift* observing campaign of XMMU J063259.3+054801 between 2009 January and 2009 April are presented in A. Falcone et al. (2009, in preparation).

The nondetection of HESS J0632+057 by VERITAS provides evidence for variability in the flux of gamma-rays with energies above 1 TeV. HESS J0632+057 is unlikely to have a blazar counterpart. Blazars are generally hard X-ray point sources and bright radio sources. Neither the XMM observation nor the Swift images show the presence of any bright X-ray source other than the Be star within the HESS error circle. A search in the NVSS catalog also finds no radio source in the area. The VHE emission and variability can be easily explained if MWC 148 would be part of a binary system and high-energy photons are produced in a similar way to that in LS I +61 303 or LS 5039. The available data do not allow any conclusion on a possible periodicity of the gamma-ray signal. A detection of the compact companion or of the orbital motion of the Be star is required to confirm or refute the binary nature of this system. Particle acceleration and VHE emission from massive stars with strong magnetic fields have also been suggested. A confirmation that MWC 148//HESS J0632+057 is surrounded by sufficiently strong magnetic fields, along with further theoretical work to explain the variability in the gamma-ray emission, would be needed to establish this potentially new class of galactic gamma-ray sources. Future multiwavelength observations combined with results from ground-based and space-based gamma-ray observatories will provide a deeper understanding of the true nature of HESS J0632+057.

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Facilities: VERITAS, *Swift*

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