HESS J0632+057: A NEW GAMMA-RAY BINARY?

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ABSTRACT

The High Energy Stereoscopic System (HESS) survey of the Galactic plane has established the existence of a substantial number (~ 40) of Galactic TeV γ-ray sources, a large fraction of which remain unidentified. HESS J0632+057 is one of a small fraction of these objects, which is point-like in nature (< 2′ rms), and is one of only two point-like sources that remain unidentified. Follow-up observations of this object with XMM-Newton have revealed an X-ray source coincident with the TeV source and with the massive star MWC 148, of the spectral type B0pe. This source exhibits a hard spectrum, consistent with an absorbed power law with $\Gamma = 1.26 \pm 0.04$, and shows significant variability on hour timescales. We discuss this spatial coincidence and the implied spectral energy distribution of this object and argue that it is likely a new γ-ray binary system with a close resemblance to the three known members of this class and, in particular, to LS I +61 303. Further, X-ray, radio, and optical observations of this system are needed to firmly establish HESS J0632+057 as a new member of this rare class of Galactic objects.

Key words: X-rays: binaries

1. INTRODUCTION

The emerging class of γ-ray binaries has three well-established members, PSR B1259 – 63/SS 2883 (Aharonian et al. 2005a) LS 5039 (Aharonian et al. 2005b, 2006c), and LS I +61 303 (Albert et al. 2006, 2008; Acciari et al. 2008), all high-mass X-ray binary systems. All these objects show variable or periodic TeV γ-ray emission with peak fluxes around $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (1–10 TeV). As such fluxes are well above the sensitivity achieved by the HESS Galactic plane survey (Aharonian et al. 2006a), the serendipitous discovery of new γ-ray binaries might be expected in HESS observations. Indeed, the TeV emission of LS 5039 was discovered in this way. Binaries are one of the few classes of sources expected to be detectable in HESS observations. Of the ~ 10 unidentified TeV sources (Hinton 2008), only HESS J1745−290 (Aharonian et al. 2006b) (at the gravitational center of the Galaxy) and HESS J0632+057 (Aharonian et al. 2007) are unresolved. For this reason alone, HESS J0632+057 can be considered as a candidate for a new binary system.

HESS J0632+057 was discovered in HESS observations of the region of apparent interaction between the Monoceros Loop supernova remnant and the star-forming regions of the Rosette Nebula. Three possible associations were suggested by the HESS collaboration for this object: the unidentified ROSAT source 1RXS J063258.4+054857, the unidentified EGRET source 3EG 0634+0521, and the massive star MWC 148 (HD 259440, spectral type B0pe). To resolve the question of the association of these three objects, and to probe the greater than 3 keV emission of the X-ray source, an XMM-Newton observation of this region was conducted in 2007, the results and implications of which are described below.

2. X-RAY OBSERVATIONS AND ANALYSIS

X-ray observations toward HESS J0632+057 were taken on the 2007 September 17 with the EPIC camera of XMM-Newton for 46 ks (observation ID 0505200101). The analysis was carried out using the XMM-Newton Science Analysis Software (SAS, version 7.1.0). The data were cleaned of a strong proton flare toward the end of the observation, resulting in a useful exposure of 26 ks during which all EPIC instruments were fully operational. The standard edetect_chain tool was used to identify 31 > 5σ point-like sources in the field of view (FOV) (see Figure 1). By far, the brightest source is that found at 6°32′59″29′′ ± 0′′01, 5°48′1″5 ± 0′′1, within the HESS J0632+057 error box and offset by 0.6′ from the position of MWC 148 (Hog et al 2000), consistent with the nominal 1σ rms absolute measurement accuracy of XMM-Newton. This object, XMUM J063259.3+054801 (source 1), exhibits an integrated signal of 2140 ± 50 counts. The source is unresolved and an upper limit on the intrinsic rms width of 1′0 (at 95% confidence) has been derived by convolving the simulated point-spread function (PSF) with an assumed Gaussian emission profile. Figure 1 illustrates the spatial relationship of source 1 to HESS J0632+057 and 1RXS J063258.4+054857.

Energy spectra for source 1 were extracted from a 25′′ circular region centered on the best-fit position for each of the EPIC CCD cameras (MOS-1, MOS-2, and PN). For background estimation, a 50–100′′ annulus around the source was used for the MOS cameras and a 75′′ circular region with an offset of 150′′ from the source was used for the PN (to avoid CCD chip edges). The resulting spectra were simultaneously fitted with an absorbed power-law model, and are shown in Figure 2. The

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8 There is evidence of a single TeV flare from Cyg X-1, but γ-ray emission from this object is not firmly established (Albert et al. 2007).
best-fit model has a photon index $\Gamma = 1.26 \pm 0.04$, a column density $N_H = (3.1 \pm 0.3) \times 10^{21} \text{ cm}^{-2}$, and a 1 keV normalization of $(5.4 \pm 0.4) \times 10^{-5} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$, with $\chi^2/\text{dof} = 27.6/27$. Whilst a single temperature black body model is strongly excluded ($\chi^2/\text{dof} = 225/27$), two temperature models provide a good fit with $kT_1 \approx 0.4 \text{ keV}$ and $kT_2 \approx 2 \text{ keV}$ ($\chi^2/\text{dof} = 15.8/25$). The deabsorbed 1–10 keV flux from the power-law fit is $(5.3 \pm 0.4) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. The count rate and hardness ratio (HR2) of 1RXS J063258.3+054857 in the 0.4–2.4 keV ROSAT band are consistent (within large statistical errors) with the power-law model for source 1. There is, however, an apparently significant excess over the model in the lower than 0.3 keV region where XMM-Newton has limited sensitivity. The catalogue position of 1RXS J063258.3+054857 lies 57$''$ from source 1. Following Voges et al. (1999), we estimate a combined statistical and systematic error of 41$''$ (65$''$) at 90% (99%) confidence. Given the consistency of the flux and spectrum in the region of overlap, the marginal positional agreement, and in the absence of any viable alternative counterpart, we tentatively identify 1RXS J063258.3+054857 with XMMU J063259.3+054801.

Figure 1. XMM-Newton combined MOS-1/MOS-2 image of the HESS J0632+057 region. Left: Gaussian-smoothed ($\sigma = 3''$) count map (logarithmic color scale) of the XMM-Newton FOV, showing the 4$\sigma$ and 6$\sigma$ significance contours of the HESS source (solid lines, reproduced from Aharonian et al. 2007), the limit on the rms extent of the TeV source (dashed circle), and the greater than 5$\sigma$ X-ray sources detected in this observation (green circles). Right: the central 2' of the same map, showing the positional uncertainty on the center of gravity of HESS J0632+057 (square marker with an error bar), MWC 148 (star), the best-fit position of XMMU J063259.3+054801 (open circle), and the ROSAT faint catalogue source 1RXS J063258.3+054857 (triangle and dashed circles for estimated 90% and 99% CL position errors, respectively).

Figure 2. Measured X-ray spectra for XMMU J063259.3+054801 from the three instruments of the EPIC camera. The histograms show the best-fit forward folded absorbed power-law model.

A search for variability of source 1 has been conducted, again using all three EPIC cameras. Figure 3 shows combined EPIC light curves for the signal and background regions described earlier. We find evidence of variability on a timescale comparable with the observation: a fit to a constant value yields a chance probability of $2 \times 10^{-9}$. The data are consistent with a linear fit which implies a decrease of $39 \pm 5\%$ in flux over the 26 ks observation. We find no evidence of a change in spectral shape when splitting the data into two 13 ks slices. With $N_H$ fixed to $3.1 \times 10^{21} \text{ cm}^{-2}$, the spectral indices of the first and second segments are $1.25 \pm 0.04$ and $1.28 \pm 0.06$, respectively. With both $N_H$ and the spectral index fixed to the full-dataset values, the best-fit normalization falls from $(6.1 \pm 0.2) \times 10^{-5} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ to $(4.6 \pm 0.2) \times 10^{-5} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ in the second slice.

3. DISCUSSION

A fundamental question in the interpretation of XMMU J063259.3+054801 is the physical process responsible for the X-ray emission. Given the existence of TeV emission from this region, it seems natural to attribute the power-law X-ray emission as synchrotron emission from ultrarelativis-
tic electrons. However, spectra resembling that observed for source 1 (consistent with two temperature blackbody models with $kT_1 \sim 0.5$ keV and $kT_2 \sim 2$ keV) have been observed for isolated magnetic Bp stars, such as σ Ori E, and been attributed to shock heating of magnetically confined winds (see Townsend et al. 2007, and references therein). It seems possible that MWC 148 is a system of this type, and that the observed X-ray emission is thermal in origin. However, it is difficult to explain the TeV γ-ray emission in such a scenario. In the discussions that follow, we assume that the observed X-ray emission is nonthermal in origin. If this is not the case, then the observed flux provides an upper limit on the nonthermal X-ray flux of HESS J0632+057.

The probabilities of chance associations of HESS J0632+057 with MWC 148 and 1RXS J063258.3+054857 have been estimated as $10^{-4}$ and $10^{-3}$ (Aharonyan et al. 2007), respectively. The chance coincidence of a massive star with the 1σ error box of the brightest (and the hardest spectrum) source in an XM-M-Newton observation is even less probable ($\sim 10^{-6}$). The least secure association is that with 3EG 0634+0521, as $\sim 10\%$ of all Galactic TeV sources lie within the 99% confidence contour of a 3EG source (Funk et al. 2008). Furthermore, the binary system SAX J0635+0533 (composed of a 34 ms period pulsar and a Be star) has been suggested to power most or all of the flux of 3EG 0634+0521 (Kaaret et al. 1999). However, as 3EG 0634+0521 is flagged as extended and/or confused it seems plausible that HESS J0632+057 may contribute to this emission. The relative contributions of these and other sources to 3EG 0634+0521 should be established by the first months of data from Fermi Gamma-ray Space Telescope. We note that there is no evidence of TeV emission from SAX J0635+0533 (Aharonyan et al. 2007).

If all the apparent associations of HESS J0632+057 are correct, then its spectral energy distribution (SED) bears a close resemblance to that of the known TeV binaries. All have hard ($\Gamma < 2$) X-ray spectra and significantly softer TeV spectra. Furthermore, X-ray variability with timescales comparable to those observed here for source 1 has been observed in LS1+61303 (Esposito et al. 2007). Associations with GeV γ-ray sources also exist in the cases of LS 5039 (3EG J1824−1514) and LS I +61 303 (3EG J0241+6103). These systems are powered by either a relativistic pulsar wind or a wind-accretion powered jet (see, e.g., Mirabel 2007). An assessment of the possible power source of HESS 0632+057 requires an estimate of the distance to the system. Using the apparent visual magnitude $m_V = 9.16$ of MWC 148 (Hog et al. 2000), assuming an absolute magnitude $M_V = -4.0$, and accounting for reddening assuming an intrinsic $M_B − M_V$ of $−0.3$, we find a distance of $\sim 1.5$ kpc, consistent with that of the Rosette Nebula (Hensberge et al. 2000). At this distance, the 1σ limit on the intrinsic size (and the similar limit on the projected displacement from MWC 148) of the X-ray source implies an origin of the emission within $\sim 2 \times 10^{16}$ cm of the star and hence a radiation density greater than $10^6$ eV cm$^{-3}$. In the presence of such a strong, high-energy (KT $\sim 3$ eV) photon field, inverse Compton (IC) scattering of TeV electrons must occur in the deep Klein-Nishina (KN) regime. IC cooling is dominant if $f_{\text{KN}}(E_\gamma) U_{\text{rad}} > U_{\text{mag}}$, where $f_{\text{KN}}(E_\gamma)$ is the suppression factor due to the KN effect. Following Moderski et al. (2005), $f_{\text{KN}}(E_\gamma) \approx (1.0 + (4 E_\gamma \times 2.8 kT)/(m_c c^2)^2)^{-1.5}$, and for $kT = 3$ eV and $E_\gamma = 1$ TeV, $f_{\text{KN}} \sim 10^{-3}$. If IC cooling in the KN regime is dominant, then a hard X-ray spectrum and softer TeV γ-ray spectrum, as observed in this case, can be expected. Such a scenario has been recently discussed for a pulsar wind nebula in the central parsec of our galaxy (Hinton & Aharonian 2007) and for binary systems such as PSR B1259 − 63/SS 2883 (Khangulyan et al. 2007).

Assuming for the moment a distance of the emission region from the star of a few AU, radiation densities of $U_{\text{rad}} \sim 1$ erg cm$^{-3}$ are expected. The relative flux of X-rays and TeV γ-rays then implies $B \sim 5 (f_{\text{KN}} F_X/F_\gamma)^{0.5} G \sim 70$ mG. For these radiation and magnetic fields, 1 TeV electrons produce X-rays of a few keV and γ-rays of almost TeV energy (if the IC scattering proceeds in the deep KN regime). The cooling time ($E/\text{d}E/\text{d}t$) for these electrons is then $\sim 20$ ks, compatible with the X-ray variability observed for source 1. Furthermore, in contrast to synchrotron-dominated cooling, the cooling timescale is almost constant with energy in the region probed by synchrotron X-rays and no spectral variability is expected, again compatible with this observation. We note that in this scenario, correlated X-ray and TeV γ-ray variability is expected.

An illustrative one-zone model with these parameters ($B = 70$ mG, $U_{\text{rad}} = 1$ erg cm$^{-3}$) is shown in Figure 4. Particles are injected with a spectrum $dN/dE \propto E^{-\alpha} \exp (-E/E_{\text{max}})$, with $\alpha = 2$ and $E_{\text{max}} = 10$ TeV, and cool continuously. The SED reaches an equilibrium state (as shown) for timescales $\gg 20$ ks. Lower values of $E_{\text{max}}$ are difficult to reconcile with the highest-energy X-ray and γ-ray data points. The effect of changing the minimum energy of injected electrons is shown in Figure 4. We note that values as high as 100 GeV (long-dashed curve) might be expected in the binary PWN scenario: Fermi Gamma-ray Space Telescope is well suited to probe this region (see the sensitivity curve in Figure 4). If genuinely associated, the flux level of 3EG 0634+0521 may represent a higher state of this variable object or indicate a softer electron spectrum in the GeV range.

The power requirements of the observed emission place limitations on the possible energy source in the system. The model shown in Figure 4 requires a power of $10^{34}$ erg s$^{-1}$. The luminosities in individual wavebands are $\sim 1.3 \times 10^{32}$ erg s$^{-1}$ (1−10 keV), $\sim 3 \times 10^{34}$ erg s$^{-1}$ (0.2−2 GeV), and $\sim 5 \times 10^{32}$ erg s$^{-1}$ (0.4−4 TeV). These luminosities should be compared to the available kinetic power of the Be-star wind ($\mathcal{O}(10^{34})$ erg s$^{-1}$; see, e.g., Waters et al. 1987), the wind accretion luminosity on to an (unseen) compact companion ($\sim 10^{35}$ erg s$^{-1}$; see Frank et al. 1992), and the spin-down power of an (unseen) young pulsar companion ($\dot{E} \approx 8 \times 10^{15}$ erg s$^{-1}$, e.g., in PSR B1259 − 63; Johnston et al. 1992).

4. SUMMARY AND OUTLOOK

It seems very likely that the sources identified as HESS J0632+057 and XMMU J063259.3+054801 originate in the same astrophysical object and that this object is associated with the Be-star MWC 148. Whilst the nature of this object remains uncertain, it is unlikely that an isolated star can provide the necessary power or accelerate particles to the required maximum energy of $\sim 1$ TeV, MWC 148 is, therefore, likely part of a binary system. By analogy with known...
Figure 4. SED of HESS J0632+057/XMMU J063259.3+054801 (red symbols/regions) compared with that of the γ-ray binary system LSI+61303 (gray symbols/regions; see Chernyakova et al. 2006 and references therein) and the estimated 1 year GLAST sensitivity for this region (thick solid line). The solid, short-dash, and long-dash curves show the synchrotron and IC components of a simple time-dependent one-zone model with $E_{\text{min}}$ set to 1 GeV, 10 GeV, and 100 GeV, respectively—see text for details.

γ-ray binaries, which exhibit similar X-ray and TeV spectra, the unseen companion of MWC 148 is likely a young pulsar or an accreting black hole or a neutron star driving a jet. The possible association of this object with 3EG 0634+0521 will be tested in the near future using Fermi Gamma-ray Space Telescope, which should achieve a source location accuracy of ≈ 100′′ after 1 year. The observed emission and variability appear consistent with synchrotron and IC emission from a population of relativistic electrons in a region within a few AU of the star. Continued radio–γ-ray monitoring of this object is proposed to establish the existence of periodicity and/or correlated variability and to confirm or refute the binary nature of this object.

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