MULTI-WAVELENGTH STUDY OF HESS J1741–302

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ABSTRACT

We present the results of two Chandra X-ray Observatory (CXO) observations of TeV γ-ray source HESS J1741–302. We investigate whether there is any connection between HESS J1741–302 and the sources seen at lower energies. One of the brightest X-ray sources in the HESS J1741–302 field, CXOU J174112.1–302908, appears to be associated with a low-mass star (possibly representing a quiescent low-mass X-ray binary or cataclysmic variable (CV)), hence, it is unlikely to be a source of TeV γ-rays. In the same field we have potentially detected X-rays from WR 98a, which is likely to be a colliding wind binary with massive stars. No TeV emission has been reported so far from such systems although predictions have been made. Finally, we found that the previously reported Suzaku source, Suzaku J1740.5–3014 (which is not covered by the CXO observations), appears to be a hard X-ray source detected by INTERGAL ISGRI, which supports the magnetized CV classification but makes its association with the TeV emission unlikely. The young pulsar PSR B1737–30, so far undetected in X-rays and projected on the sky near the CV, may be the contributor of relativistic particles responsible for the TeV emission.

Key words: gamma-rays: general – ISM: individual objects (HESS J1741–302) – X-rays: general – X-rays: individual (Suzaku J1740.5–3014, Suzaku J1741.4–3006)

1. INTRODUCTION

The High Energy Stereoscopic System (HESS) has revealed many TeV γ-ray sources in the Galactic plane (Aharonian et al. 2005). Roughly half of the total number of sources in the Galactic plane (∼90) have been firmly associated with high-mass X-ray binaries (HMXBs), shell-type supernova remnants (SNRs), and pulsar-wind nebulae (PWNe). The latter appear to dominate the overall population of Galactic TeV sources (see Kargaltsev et al. 2013 for review). There is a substantial number of unidentified very high energy (VHE; detected above 1 TeV) sources (∼20), some of which have plausible multi-wavelength (MW) counterparts (e.g., nearby young pulsars) but the associations have not been confidently established yet (e.g., there is no X-ray PWN, X-ray, and TeV emission do not correlate, offsets from pulsars are too large). Finally, there are few (∼7) VHE sources that belong to so-called “dark accelerators” because they have no plausible counterparts at any other wavelength (see Kargaltsev et al. 2013). It was suggested that these VHE sources could be relic PWNe of older undetected pulsars (see e.g., de Jager et al. 2009; Tibolla et al. 2011; Vorster et al. 2013).

HESS J1741–302, located near the Galactic center, was discovered during a HESS survey of the Galactic plane (Tibolla et al. 2008). This source was detected with a significance of 8.1σ in 143.5 hr of observations (Tibolla et al. 2009). The TeV image of the source appears to exhibit two hot spots which, due to poor statistics, could not be definitively claimed to be two independent sources (Tibolla et al. 2009). In this paper we tentatively label these hot spots as HESS J1741–302A and HESS J1741–302B (hereafter J1741A and J1741B, respectively; see Figure 1). We define the HESS J1741A region as a 4′2 circle at a position of R.A. = 17h41m40s and decl. = −30°05′00″ and the HESS J1741B region as a 6′4 circle at a position of R.A. = 17h41m17s and decl. = −30°23′00″, based on Figure 5 from Tibolla et al. (2009). Two scenarios have been put forth to describe the emission from HESS J1741–302, namely hadronic gamma-ray production via interaction of cosmic rays with molecular clouds in the region, or a PWN associated with the offset, yet relatively young and powerful, pulsar B1737–30 (Tibolla et al. 2009).

There have been previous efforts to find a MW counterpart of HESS J1741–302. Matsumoto et al. (2010) and Uchiyama et al. (2011) have analyzed two Suzaku observations, covering both J1741A and J1741B, to search for X-ray counterparts. Matsumoto et al. (2010) claimed to have detected an X-ray counterpart of J1741A (see Figure 2 from Matsumoto et al. 2010) with the XIS spectrum fitted by an absorbed power-law (PL) model with photon index Γ = 1.13 ± 0.6 and intervening hydrogen column N_H = (3.95 ± 2.7) × 10^{22} cm^{-2}. The observed X-ray flux of Suzaku J1741.4–3006 (hereafter, Suzaku J1741) in the 2–10 keV band, \( F_{2–10\text{keV}} = 3.2 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2} \), corresponds to a TeV to X-ray flux ratio of \( F_{\gamma–10\text{TeV}} / F_{2–10\text{keV}} \sim 6 \). Based on the high TeV to X-ray flux ratio, Matsumoto et al. (2010) suggested a hadronic origin of the TeV γ-ray emission from J1741A. The extent of Suzaku J1741 (∼5′) is based on the X-ray contours shown in Figure 2 of Matsumoto et al. (2010), which suggests that the source is resolved by Suzaku XIS into diffuse emission. The Suzaku observation covering J1741B also revealed an X-ray source, Suzaku J1740.5–3014 (hereafter, Suzaku J1740). The detected periodicity of 432.1 ± 0.1 s together with the X-ray spectrum showing Fe Kα emission, suggests that the source is a magnetic cataclysmic variable (CV), most likely an intermediate polar (Uchiyama et al. 2011). Intermediate polars are not known (or expected) to produce VHE emission, making Suzaku J1740 an unlikely counterpart of the TeV source if the observed X-ray emission solely comes from the CV.

Three pulsars located in the field of HESS J1741–302 are shown in Figure 1. Of those three, PSR B1737–30 (hereafter B1737), with a characteristic age of 20.6 kyr, distance 5.5 kpc,
and spin-down energy loss rate $\dot{E} = 8.2 \times 10^{34}$ erg s\(^{-1}\) (Johnston et al. 2001; Yuan et al. 2010), is a powerful source of relativistic particles.\(^4\) Matsumoto et al. (2010) and Uchiyama et al. (2011) reported no X-ray emission coincident with the pulsar’s location, however, the pulsar, if close enough to the CV position (which is only approximate\(^5\)), could be masked in the XIS images by the bright CV emission. Because of the large ($\approx 12\)\(^\circ\) offset of the pulsar from the peak of the TeV emission of J1741B, one needs to investigate and exclude other possible counterparts before declaring J1741B a relic PWN candidate associated with B1737. Another pulsar, PSR J1741–3016, which is significantly closer to J1741B, has a characteristic age of $3.3 \text{ Myr}$, distance $5.02 \text{ kpc}$, and much smaller $\dot{E} = 5.2 \times 10^{31}$ erg s\(^{-1}\) (Taylor & Cordes 1993; Morris et al. 2002). Therefore, this pulsar is too old to sustain a detectable PWN both in X-rays and TeV (Tibolla et al. 2009).

The PWN of the third pulsar, PSR J1739–3023, with a characteristic age of $159 \text{ kyr}$, distance $3.41 \text{ kpc}$, and $\dot{E} = 3.0 \times 10^{32}$ erg s\(^{-1}\) (Taylor & Cordes 1993; Morris et al. 2002) could be the source of TeV $\gamma$-rays but the pulsar is very offset ($\approx 24\)\(^\circ\)$ from J1741B; see Figure 1), which makes it a very unlikely counterpart unless it is a very fast moving pulsar or the ISM density is strongly non-uniform, creating the right environment for the host SNR reverse shock to expand asymmetrically (the SNR is not seen in the VLA survey images\(^6\), which could be due to the advanced age of the SNR).

To better understand the nature of J1741B we have carried out a Chandra X-ray Observatory (CXO) observation of J1741B and also retrieved an archival CXO observation of the J1741A field. Here we present the analysis of both observations including the MW analysis of the X-ray sources seen in the J1741A/B fields. We classify detected X-ray sources and investigate the origin of different sources seen in this region at lower energies. We discuss whether any of these sources could be responsible for the TeV emission.

This paper is organized as follows. Section 2 summarizes the X-ray observations and data reduction, Section 3 discusses the search for MW counterparts of the detected X-ray sources, Section 4 presents the results from the analysis of the MW data, and Section 5 summarizes our findings. Section 6 is an Appendix describing the details of our MW classification tool.

2. CXO OBSERVATIONS AND DATA REDUCTION

Two CXO observations, ObsIDs 9976 (PI Tibolla; 19.7 ks exposure) and 13790 (PI Kargaltsev; 44.4 ks exposure), of HESS J1741–302 were used in our analysis, covering the fields of J1741B and J1741A, respectively. In both observations the data were taken with the ACIS-I instrument operated in “Very Faint” Target exposure mode. We processed the data using the CXO Interactive Analysis of Observations (CIAO\(^7\)) software (version 4.6) and CXO Calibration Database version 4.5.9. We restricted our analysis to the energy range of 0.5–7 keV. We used CIAOs Mexican-hat wavelet source detection routine wavdetect (Freeman et al. 2002) to detect X-ray sources and measure their coordinates in the CXO images (see Table 1 and Figure 2). CIAO’s task srcflux was used to calculate the observed source fluxes. For the brightest sources, the X-ray spectra and responses were extracted using standard CIAO procedures. The X-ray spectra were binned to a minimum of 10 counts per bin before fitting. Fits to X-ray spectra were performed using XSPEC 12.8.2.

In order to look for extended sources the CIAO tool vtpdetect was run on the 0.5–7 keV band image. No extended sources were found. We also created a “fluxed” image by

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\(^4\) This pulsar is also notable for the large number of glitches ($\approx 20 \text{ in } 20 \text{ years}$; see Yuan et al. 2010 and references therein).

\(^5\) The offset between the pulsar and the CV positions could be $\approx 0.3 \pm 0.5^\circ$ due to a large uncertainty in the Suzaku pointing accuracy. The uncertainty is difficult to correct for due to the presence of only three very faint sources (in addition to Suzaku J1740) in the XIS images and the very high density of 2MASS sources in this region. It is unclear from (Uchiyama et al. 2011) how the $90^\circ$ offset was determined from matching these X-ray sources with 2MASS stars despite the confusion caused by the high density of NIR sources.

\(^6\) http://archive.nrao.edu/nvvis/

\(^7\) http://cxc.harvard.edu/ciao/index.html
Table 1

| #  | CXOUa | Field   | R.A. b | Decl. b | Fb | Countsd | HRc | Classd (%) |
|----|-------|---------|--------|---------|----|---------|-----|------------|
| 1  | J174119.6–300745 | J1741A | 17°41′19″56 | −30°07′45″1 | 1.8 ± 0.5 | 33 | 0.95 | AGN (84) |
| 2  | J174120.0–300647 | J1741A | 17°41′28″00 | −30°06′47″7 | 4.4 ± 0.9 | 71 | 0.99 | ? |
| 3  | J174123.9–300528 | J1741A | 17°41′23″95 | −30°05′28″2 | 2.6 ± 0.8 | 36 | 0.91 | AGN (87) |
| 4  | J174126.6–300525 | J1741A | 17°41′26″61 | −30°05′25″5 | 5 ± 1 | 90 | 0.95 | AGN (78) |
| 5  | J174133.0–300453 | J1741A | 17°41′33″04 | −30°04′53″2 | 3.1 ± 0.8 | 40 | 0.99 | ? |
| 6  | J174121.8–300912 | J1741A | 17°41′28″83 | −30°09′12″5 | 2.4 ± 0.8 | 33 | 0.95 | ? |
| 7  | J174116.6–303015 | J1741A | 17°41′16″66 | −30°03′15″1 | 1.7 ± 0.5 | 43 | 0.82 | ? |
| 8  | J174146.1–391926 | J1741A | 17°41′46″16 | −30°10′26″3 | 3.3 ± 0.9 | 47 | 0.99 | ? |
| 9  | J174047.8–300916 | J1741A | 17°40′47″84 | −30°09′16″0 | 6.5 ± 0.8 | 201 | −0.54 | STAR (95) |
| 10 | J174045.8–300654 | J1741A | 17°40′45″85 | −30°06′54″3 | 7 ± 1 | 160 | 0.52 | ? |
| 11 | J174148.1–300039 | J1741A | 17°41′48″18 | −30°00′39″3 | 9 ± 2 | 89 | 0.91 | ? |
| 12 | J174118.1–399725 | J1741A | 17°41′18″19 | −30°07′25″5 | 0.6 ± 0.2 | 33 | −0.87 | STAR (92) |
| 13 | J174112.1–302908 | J1741B | 17°41′12″13 | −30°29′08″4 | 11 ± 2 | 113 | 0.91 | ? |
| 14 | J174115.2–302434 | J1741B | 17°41′15″25 | −30°24′34″8 | 2.7 ± 0.6 | 68 | −0.87 | STAR (97) |
| 15 | J174113.0–303230 | J1741B | 17°41′13″04 | −30°32′30″7 | 9 ± 1 | 104 | 0.61 | ? |
| 16 | J174125.3–302853 | J1741B | 17°41′25″30 | −30°28′53″8 | 11 ± 3 | 54 | 0.91 | ? |
| 17 | J174102.7–302525 | J1741B | 17°41′02″77 | −30°25′25″9 | 3 ± 1 | 23 | 0.91 | AGN (85) |
| 18 | J174052.7–302737 | J1741B | 17°40′52″73 | −30°27′37″7 | 4 ± 1 | 32 | 0.95 | ? |
| 19 | J174054.4–301933 | J1741B | 17°40′54″43 | −30°19′33″4 | 1.8 ± 0.5 | 45 | −0.83 | STAR (97) |

Notes.

a Source name according to the standard Chandra source naming convention.

b Coordinates are listed for the J2000 epoch.

c Observed X-ray fluxes in the 0.5–7 keV range in units of 10⁻¹⁴ erg s⁻¹ cm⁻².

d Number of counts in the 0.5–7 keV range.

e Hardness ratio calculated as (H – M – S)/(H + M + S), where S, M, and H are the number of counts in the 0.5–2.0 keV, 1.2–2.0 keV, and 2.0–7.0 keV bands, respectively.

f Classification and its confidence according to the automated classification algorithm (see the Appendix).

f’ “?” denotes cases with less confident (<70% confidence) classifications.

Figure 2. CXO/ACIS-I images of ObsId 13790 (J1741A field; left panel) and 9976 (J1741B field; right panel) with 19 X-ray sources detected (Table 1) in the 0.5–7.0 keV energy band. North is up and right is east. Gaussian smoothing with a kernel radius of 3″ was applied to each image. The red circles show the extent of the source detected by Suzaku (Matsumoto et al. 2010).

subtracting the point sources and replacing them with the local background using the dmfilth CIAO tool⁸ and then dividing by the exposure map, but no signs of diffuse emission are seen at various binning and smoothing scales.

⁸ http://cxc.harvard.edu/ciao/threads/diffuse_emission/

We have detected 12 and 7 X-ray point sources in the fields of J1741A and J1741B, respectively, at a significance level >4σ (Table 1). For the brightest sources in each field the spectra were extracted from a 3″ radius circle for source 13 and 7″ radius circles for the other sources because they were imaged at large off-axis angles (see Table 1). For each of these
sources spectra we fitted absorbed PL and absorbed blackbody (BB) models (except for sources 9 and 10; see below), with \( N_H \) fixed to the galactic value. The spectrum of source 9 was fitted with a MEKAL model (Mewe et al. 1986), instead of a PL model, with the absorption as a free parameter (because other fits failed). All fits used the XSPEC phabs model (Balucinska-Church & McCammon 1992) for interstellar absorption. Best-fit parameters for each model can be found in Table 2, while the spectra and the fits are shown in Figure 3.

### 3. MW COUNTERPART SEARCH

We collected the MW properties (0.5–2.0 and 2.0–7.0 keV fluxes, two hardness ratios, optical, NIR, and IR photometry) of the 19 sources detected in the ACIS-I images. The photometry was taken from optical (USNOB; Monet et al. 2003), NIR (Two Micron All Sky Survey; 2MASS; Skrutskie et al. 2006), and IR (Spitzer, Wide-field Infrared Survey Explorer (WISE); Fadda et al. 2006; Cutri et al. 2012) surveys. Only 8 of the 19 total sources in both fields were found to have MW counterparts in these surveys. The optical, NIR, or IR source was considered to be a counterpart of an X-ray source if their positions are within 2″ of each other. For each survey we calculate the chance superposition based on the average optical/NIR/IR source densities in the field (\( \rho = 0.00249, 0.0108, \) and 0.00187 sources arcsec\(^{-2} \)) in the USNO-B1, 2MASS, and WISE surveys, respectively). We calculate the probability of finding zero field sources in the circle of radius \( r = 2\alpha, \) as \( P = \exp(-\rho r^2). \) Therefore, the probabilities of each counterpart being due to chance are coincidence are \( 1 - P = 3.1\%, 12.7\%, \) and 2.3\% (for the USNO-B1, 2MASS, and WISE surveys, respectively). The chance coincidence probability is highest for 2MASS where we expect up to two of the cross-matches to possibly be spurious. None of the 19 sources have more than one MW counterpart within 2″ of their X-ray position. The IR/NIR/optical magnitudes of the potential counterparts are listed in Table 3.

We used this MW information together with the measured X-ray properties to classify these 19 sources. Using two different machine-learning methods described in the Appendix, 10 sources were classified with >70% confidence by at least 1 of the algorithms and, of these, 8 had consistent (>70%) classifications by both algorithms. Below we only report the results consistent across both methods. The eight classifications with confidence >70% shown in Table 1, include four active galactic nuclei (AGNs) and four stars.

### 4. RESULTS AND DISCUSSION

#### 4.1. HESS J1741–302a

Our analysis of the CXO image (ObsID 13790), which covers the J1741A region, reveals a number of X-ray point sources with no trace of diffuse emission (Figure 2, left...
down to a surface brightness limit of \( \sim 2.5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2} \) in the 0.5–7 keV band. This limit is based on an absorbed PL model (with \( \Gamma = 1.5 \) and \( N_{\text{H}} = 1.47 \times 10^{22} \text{ cm}^{-2} \)) that was used to simulate\(^{12}\) a flux corresponding to the measured 1\(\sigma\) excess of background-subtracted counts from the Suzaku J1741 region (shown in Figure 2) after the point source removal (see Section 2). The large apparent extent of the X-ray source in the Suzaku XIS images can be explained by multiple faint point sources seen in the ACIS-I image (labeled 1–6 and source 12 in Figure 2, left panel), which have been smeared out by the broad point-spread function (PSF) of the Suzaku XRT. The total observed flux

\(^{12}\) With PIMMS v.4.7b; see http://cxc.harvard.edu/toolkit/pimms.jsp

Figure 3. ACIS spectra for sources 9 (Mekal; upper left), 10 (PL; upper right), 13 (BB; lower left), and 15 (BB; lower right) in the fields of J1741A/B (the ISM hydrogen column density is fixed at the Galactic value in this direction, \( N_{\text{H}} = 1.47 \times 10^{22} \text{ cm}^{-2} \); Dickey & Lockman 1990). The fit parameters can be found in Table 2.

| #  | Field   | b\(^a\) | r\(^a\) | i\(^a\) | j\(^a\) | h\(^a\) | k\(^a\) | w\(^1\) | w\(^2\) | w\(^3\) |
|----|---------|---------|---------|--------|--------|--------|--------|--------|--------|--------|
| 2  | J1741A  | ...     | ...     | ...    | 15.835 | 13.537 | 12.859 | ...    | ...    | ...    |
| 7  | J1741A  | ...     | 19.4    | 16.68  | 12.738 | 11.312 | 10.686 | ...    | ...    | ...    |
| 9  | J1741A  | 15.14   | 13.54   | 12.6   | 11.985 | 11.446 | 11.115 | ...    | ...    | ...    |
| 12 | J1741A  | 13.48   | 12.39   | 11.81  | 11.419 | 11.038 | 11.04  | ...    | ...    | ...    |
| 13 | J1741B  | ...     | 17.47   | 14.11  | 10.3   | 9.053  | 8.434  | 7.571  | 6.854  | 5.487  |
| 14 | J1741B  | 16.04   | 14.34   | 13.67  | 12.887 | 11.796 | 11.787 | ...    | ...    | ...    |
| 15 | J1741B  | 18.40   | 15.20   | ...    | 9.143  | 6.505  | 4.332  | 6.552  | 6.188  | 2.824  |
| 19 | J1741B  | 12.64   | 12.06   | 11.86  | 10.944 | 10.75  | 10.631 | 9.567  | 9.585  | 7.422  |

Notes. “...” corresponds to the lack of a counterpart at the corresponding wavelength within the \( r = 2'' \) circle centered on the X-ray source.

\(^{a}\) Magnitudes taken from the USNO-B optical catalog (Monet et al. 2003).

\(^{b}\) Magnitudes taken from the Two-micron All Sky Survey (2MASS; Skrutskie et al. 2006).

\(^{c}\) Magnitudes taken from the Wide-field Infrared Survey Explorer (WISE; Cutri et al. 2012).
from sources 1 to 6 and 12 is \( F_X \approx 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \), comparable to the Suzaku XIS flux reported for the Suzaku source (Matsumoto et al. 2010). Our MW classification suggests that sources 1, 3, and 4 are AGNs (classification confidence is 84%, 87%, and 78%, respectively), which could, in principle, be responsible for the TeV \( \gamma \)-rays. However, the AGNs\(^\text{13}\) that emit at TeV energies typically have X-ray to TeV \( \gamma \)-ray flux ratios \( 2\)–\(3 \) orders of magnitude higher than those derived from the X-ray fluxes for these AGN candidates \( (F_{2\text{-}10\text{ keV}}/F_{\text{TeV}} = 0.01\)–\(0.03) \), thus making these sources unlikely counterparts for the TeV source (see Kargaltsev et al. 2007).

Our classification algorithm was unable to confidently classify source 2 (due to missing MW information in six bands), while the source is too faint (71 counts in ACIS-I) to meaningfully fit its X-ray spectrum. However, there is a clear deficit of soft X-rays from this source, suggesting that the spectrum is either very hard (typical of AGNs and some X-ray binaries) or, alternatively, the source is intrinsically absorbed (could be either a remote quiescent XRB or an AGN). If this source is an AGN, it still has too low of an X-ray to TeV flux ratio \( (F_{\text{X-ray}}/F_{\text{TeV}} = 0.02) \) to be a plausible candidate of the TeV source (see above). Alternatively, the source could be an XRB on the other side of the Galaxy, with large absorption making it appear faint and hard. However, typical \( \gamma \)-ray binaries have X-ray to TeV flux ratios between \( \sim 0.5 \) and 12 (Kargaltsev et al. 2014), making this source an unlikely \( \gamma \)-ray binary candidate. Furthermore, a faint NIR counterpart is found in the 2MASS survey for this source (see Table 3) with no optical counterpart, suggesting that this could be an extincted and remote low-mass X-ray binary (LMXB). Similar systems are known (e.g., XTE J1550–564; see Table 2 in Chaty et al. 2011), but are typically much brighter in X-rays (although there are some exceptions; see e.g., Padilla et al. 2014). In any case, LMXBs are not known to emit TeV \( \gamma \)-ray emission.

We have also extracted the spectra of the two brightest sources (9 and 10, in Tables 1 and 2) in this field and fitted them. The spectrum for source 9 can be described by amekal model (although the fit is not perfect) with a temperature of \( \sim 0.7 \) keV (see Table 2), suggesting the X-ray emission can come from coronal activity in a star. Source 10’s spectrum is well fit by an absorbed PL model with photon index \( \Gamma = 2.7 \pm 0.3 \). For both sources 9 and 10 a BB model provided an unacceptable fit. The lack of an optical or NIR counterpart to source 10 rules out a nearby coronally active low-mass star classification for this source but also does not allow for a definitive classification. The source could be a remote and extincted AGN. A strongly absorbed middle-aged pulsar with thermal emission dominating below 2 keV is also an option. In the latter case it could be that the relic PWN of this pulsar is powering the TeV emission. However, no extended radio emission is seen in the archival VLA images or the X-ray images near this source. The classification algorithm confidently identified source 9 as a star (95% confidence), while source 10 was not decisively classified.

4.2. HESS J1741−302B

Matsumoto et al. (2010) report the discovery of X-ray source Suzaku J1740, which is just outside the field of view in both CXO observations. The analysis of the X-ray properties suggests that this source is likely a magnetic CV (Uchiyama et al. 2011). On the sky, Suzaku J1740 may be located in the immediate vicinity of PSR B1737−30. Therefore, PSR B1737−30 may be contributing to the observed X-ray emission from the binary, if it cannot be separated from the CV emission due to the broad PSF of Suzaku XRT. The lack of CXO data precludes pinpointing the precise position of the CV and confidently distinguishing the CV emission from that of PSR B1737−30 or its PWN. An additional CXO observation is needed to isolate and study these two sources.

The automated MW classification suggests that source 17 is an AGN with fairly low X-ray flux, which makes it an unlikely counterpart to the TeV source (see above). The other two confidently classified sources (\# 14 and 19) appear to be stars. Four X-ray sources lack confident classifications. Of these, sources 13 and 15 are sufficiently bright to perform spectral fits (see Figure 3). Both sources are best-fit by an absorbed BB model and the best-fit parameters are given in Table 2. Neither source is confidently classified by our automated pipeline. The optical/NIR/IR magnitudes for the possible MW counterparts of sources 13 and 15 are listed in Table 3.

The candidate optical/NIR/IR counterpart of source 13 exhibits very red colors (see Table 3). This reddened r-band magnitude makes the optical to X-ray flux ratio unusually large for a typical AGN (see also Figure 4 in Hasinger et al. 2002). Prior to any reddening the optical/NIR/IR spectrum resembles that of a very cool star (L dwarf) which must then be very nearby (few tens of parsecs). However, the source does not exhibit any measurable proper motion\(^\text{14}\) and the X-ray fit suggests substantial extinction (which perhaps could be intrinsic for a cool brown dwarf). The uncertainty in the extinction, the unknown distance, and poor quality of the X-ray spectrum also leave a heavily obscured AGN as an option. However, an r-band magnitude of 17.47, when dereddened by \( E(B-V) = 2.94 \) (corresponding to the total galactic absorption of \( N_H = 1.47 \times 10^{22} \text{ cm}^{-2} \);Dickey & Lockman 1990), becomes 10.3. This would correspond to an extremely large optical to X-ray flux ratio \( (f_X/f_X \sim 700) \) which is typical for a cool star and atypical for AGNs. Therefore, the MW properties of source 13 are puzzling and it is not surprising that the automated classifier is confused. Of course, there always remains a small chance that the optical/NIR/IR source is not the true counterpart of the X-ray source 13.

Source 15 has a possible optical and NIR counterpart and can be seen in the Spitzer image in Figure 1. It has a known classification of WR star (known as WR 98a) (Cohen et al. 1991). WR 98a is at a distance of \( \sim 1.9 \) kpc (Monnier et al. 1999), which corresponds to an X-ray luminosity of \( 3.8 \times 10^{31} \text{ erg s}^{-1} \). Our classification algorithm was unable to confidently classify this source. However, WR 98a is surrounded by a dusty pinwheel nebula (Monnier et al. 1999). This is indicative of a tight binary which may contain two high-mass stars with strong colliding winds (Monnier et al. 1999). It is likely that the automated algorithm is confused by this, as it does not have colliding wind WR binaries as a separate class. Interestingly, it was suggested that such binaries could be TeV sources (see Aliu et al. 2008; Torres et al. 2009; Paredes 2010 and references therein) but none have been detected so far.

\(^{13}\) http://tevcat.uchicago.edu/

\(^{14}\) According to the PPMXL catalog of positions and proper motions by Roeser et al. (2010).
5. SUMMARY AND OUTLOOK

Our MW classification of 19 sources from two CXO observations did not yield an obvious candidate for the TeV emission from J1741A/B. Our automated machine learning classification algorithm relatively confidently classified eight sources (four AGNs and four Stars). However, HESS J1741–302 is not likely an AGN due to the low X-ray to TeV flux ratios, while non-degenerate coronally active stars do not emit TeV γ-rays. Sources 2, 10, and 13 could be obscured AGNs or remote XRBs while source 10 could also be a new middle-aged pulsar. Source 15 in the field of J1741B has a known WR star (WR 98a) within the CXO error ellipses, which is likely a binary, raising the intriguing possibility of the first detection of such a system in TeV γ-rays. For the J1741A region we also cannot rule out TeV emission from the star-forming clouds (see the Spitzer image in Figure 1) that provide a dense environment and enhanced IR photon background. This would still require a source of relativistic protons or electrons at the same distance. Suzaku J1741, which appears to be extended in the Suzaku image, and was previously mentioned as a plausible counterpart to J1741A, is resolved by CXO into a number of faint point sources, none of which look particularly promising as counterparts for the TeV emission. No diffuse emission is seen in the CXO image. The analysis of MW data also did not produce any credible counterparts. The INTEGRAL flux enhancement near the position of Suzaku J1740 is consistent with the proposed magnetic CV nature, which implies no TeV emission. However, the PWN of the young radio pulsar B1737–30, located outside of the CXO field of view, also remains a possible counterpart for the TeV source.

Further observations of this field, including the three pulsars, are needed to look for possible offset PWNe from PSR J1739–3023 or PSR B1737–30. These observations would also enable us to spatially resolve the X-ray emission from PSR B1737–30 and CV Suzaku J1740. Future TeV observations will also help build enough statistics to determine whether there are two separate sources or only one larger extended source and further constrain the TeV spectrum. Until the contributions from the relic PWNe associated with the two pulsars are ruled out the source can hardly be on the list of “dark accelerators;” assuming that the “dark accelerator” term is reserved for TeV sources lacking any plausible counterparts in a reasonable vicinity.

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APPENDIX

Our supervised machine-learning pipeline relies on two supervised decision tree learning algorithms and a training data set. We use the See5 implementation15 of the C5 decision tree algorithm (Quinlan 1993) and a Random Forest16 classifier (Breiman 2001).

The algorithms determine the degree of similarity between the sources from the training data set and unclassified sources using a number of MW parameters. All unclassified X-ray sources are cross-matched with MW catalogs in order to extract the MW parameters similar to those used in the training data set described below (see Section 3 for the spatial selection criteria for MW counterparts). The following MW parameters are extracted: X-ray fluxes in four bands and two hardness ratios from the CXO observations17, optical u, g, r, i, z magnitudes from the UNSO-B catalog (Monet et al. 2003), NIR j, h, k magnitudes from the 2MASS (Cutri et al. 2006) and IR W1, W2, W3 magnitudes from WISE (Cutri et al. 2012).

The training data set we used here has ~ 8500 sources with nine predefined object classes: (1) main sequence stars (General Catalog of Variable Stars; Samus et al. 2009), (2) young stellar objects (Chandra Orion Ultradepth Point Source Catalog and PAN-Carina; Getman et al. 2005; Povich et al. 2011), (3) AGNs (Veron Catalog of Quasars & AGN; Véron-Cetty & Véron 2010), (4) LMXBs (Low-mass X-ray Binary Catalog, 2007; Liu et al. 2007), (5) HMXBs (Catalog of High-mass X-ray Binaries in the Galaxy; Liu et al. 2006), (6) CVs (Cataclysmic Variables Catalog, 2006, Downes et al. 2001), (7) isolated neutron stars (NSs; ATNF Pulsar Catalog; Manchester et al. 2005), (8) binary non-accreting NS (ATNF Pulsar Catalog), and (9) WR stars (the VIIIth Catalog of Galactic WR Stars; van der Hucht 2001). All of the AGNs in our training data set are located off of the galactic plane. Therefore, these AGNs will look different from those in our observations due to galactic absorption. In order to correct for this, all AGN parameters in the training data set were reddened using the total galactic absorption column in the direction of our observations (N_H = 1.47 × 10^{22} cm^{-2}; Dickey & Lockman 1990).

A Laplace prescription for the estimation of the classification confidences18, P, has been adopted (Chawla 2002). For each leaf node, P = (TP + 1)/(TP + FP + C), where TP, FP, and C are true positives, false positives, and number of classes, respectively, for the leaf in which the source question has landed based on its parameters.

To check the accuracy of both algorithms, we have used two fold cross-validation. This involves dividing the training data set into two parts and then training the algorithms on this first half. The second half is then classified by the algorithms and then compared to their real classifications. The accuracy scores of C5 and Random Forest were ~90% and 93%, respectively.

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15 http://www.rulequest.com/see5-unix.html
16 http://scikit-learn.org/stable/modules/ensemble.html
17 The energy bands were chosen to be the same as those used in the Chandra Source Catalog.
18 Note that the calculated confidences do not include the uncertainties in the X-ray flux, which can be significant for faint X-ray sources and will impact the HRs. Source confusion (i.e., the possibility of assigning a false MW counterpart to an X-ray source) is also not accounted for in the confidence calculation.
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