HIGH-ENERGY X-RAYS FROM J174545.5–285829, THE CANNONBALL: A CANDIDATE PULSAR WIND NEBULA ASSOCIATED WITH Sgr A EAST

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ABSTRACT

We report the unambiguous detection of non-thermal X-ray emission up to 30 keV from the Cannonball, a few-arcsecond long diffuse X-ray feature near the Galactic Center, using the NuSTAR X-ray observatory. The Cannonball is a high-velocity (v ≈ 500 km s⁻¹) pulsar candidate with a cometary pulsed wind nebula (PWN) located ~2° north–east from Sgr A*, just outside the radio shell of the supernova remnant Sagittarius A (Sgr A) East. Its non-thermal X-ray spectrum, measured up to 30 keV, is well characterized by a Γ ≈ 1.6 power law, typical of a PWN, and has an X-ray luminosity of L(3–30 keV) = 1.3 × 10³⁴ erg s⁻¹. The spectral and spatial results derived from X-ray and radio data strongly suggest a runaway neutron star born in the Sgr A East supernova event. We do not find any pulsed signal from the Cannonball. The NuSTAR observations allow us to deduce the PWN magnetic field and show that it is consistent with the lower limit obtained from radio observations.

Key words: Galaxy: center – ISM: individual objects (Sagittarius A, Sagittarius A East) – ISM: supernova remnants – stars: neutron – X-rays: individual (Cannonball)

1. INTRODUCTION

Sagittarius A (Sgr A) East is an elongated non-thermal radio shell, which in the West encompasses Sgr A* and Sgr A West, and in the East is bounded by a molecular cloud with which it is likely interacting. The region interior to the shell emits thermal X-rays. Park et al. (2005) (hereafter P05), using data from Chandra observations, found the X-ray emission comes from three distinct regions: a Center region highly enriched in Fe and other elements; a North region more modestly enriched from three distinct regions: a Center region highly enriched in Fe and other elements; and a “Plume” region with solar abundances. Each region lies the North–South direction, suggesting a cometary tail pointing back to the approximate center of Sgr A East (P05). Based on its non-thermal X-ray emission, spatial extent (~0.1 pc at 8 kpc), association with Sgr A East, and lack of flux variation on year timescales, CXOGC J174545.5–285829 has been proposed as a runaway neutron star (NS) with a pulsar wind nebula (PWN). However, due to the lack of spectral coverage above 8 keV, Chandra was unable to resolve a high-temperature thermal model, such as what would be found in a cataclysmic variable, from a non-thermal spectrum typical of a PWN. So far, pulsations remain undetected.

The radio observations present a similar picture. A radio counterpart to the Cannonball is detected at 5.5 GHz (Zhao et al. 2013, hereafter ZMG13) that connects to a radio plume region (~30″ × 15″) and a long radio tail (~30″) trailing from the radio shell back into the interior of Sgr A East. This morphology is similar to that observed for several runaway NSs (e.g., the Mouse; Gaensler et al. 2004). The proper motion, implying a transverse speed of ~500±100 km s⁻¹, flat spectrum (α ≈ −0.44 ± 0.08 for the compact head, S_n ∝ νⁿ), and the cooling linear tail (α ≈ −1.94 ± 0.02; ZMG13) all strongly suggest that the Cannonball is a PWN associated with a NS that has overrun the shell of Sgr A East. Here we report the NuSTAR discovery of non-thermal X-rays from the Cannonball up to energies 30 keV. In Section 2 we describe the NuSTAR observations. In Sections 3–5 we present the imaging, spectral and timing analysis, respectively. In Section 6, we use NuSTAR and Chandra data to estimate the PWN magnetic field strength independent of the lower limit derived from the radio observations of ZMG13.
2. NuSTAR OBSERVATIONS

NuSTAR is the first focusing telescope that operates in the hard X-ray band of 10–79 keV. It consists of two coaligned optics/detector pairs, focal plane modules A and B (FPMA and FPMB), and has a field of view of 10′ × 10′ at 10 keV. NuSTAR has an angular resolution of 18′′ FWHM and 58′′ half power diameter, and an energy resolution of 400 eV (FWHM) at 10 keV (Harrison et al. 2013). The nominal NuSTAR timing resolution is 4 ms. The nominal NuSTAR reconstruction coordinates are accurate to 8″ (90% confidence level). In the following study, all observation were processed using nupipeline, NuSTARDAS v. 1.1.1, which is used to generate response matrices and exposure maps, and the HEASoft v. 6.13 package was used for data analysis.

NuSTAR observed Sgr A* three times between 2012 July 20 and 2012 October 10 (Barriero et al. 2013). In addition, NuSTAR triggered multiple target of opportunity (ToO) observations, four of which were used in the subsequent analysis, of the outburst from the newly discovered magnetar SGR J1745–29 near Sgr A* in 2013 (Mori et al. 2013). The Cannonball, located ∼2′ away from Sgr A*, was captured in the NuSTAR field of view in all seven observations, with a total exposure time of 429 ks (Table 1). We performed imaging and spectral analysis using the three Sgr A* observations, as the Cannonball falls on or near the detector chip gaps in the SGR J1745–29 observations, which were otherwise suitable for timing analysis. Photon arrival times were corrected for on-board clock drift and precessed to the solar system barycenter using the JPL-DE200 ephemeris and sgr A* observations using a 20″ radius circular region centered on the Chandra position (P05).

3. IMAGING ANALYSIS

We applied astrometric corrections to each NuSTAR event file by aligning NuSTAR-detected objects with their reference Chandra locations (Muno et al. 2003). This is particularly important in the crowded Galactic Center region as it increases the significance of faint sources. We then generated a mosaiced NuSTAR image of the Cannonball by merging exposure-corrected images from each observation. The resulting 3–79 keV mosaic is shown in Figure 1, along with the 3–8 keV Chandra contours (P05). It is clear that the Chandra contours are centered on the bright Cannonball emission in the NuSTAR image. The 10–30 keV NuSTAR image is shown as an inset. The Cannonball is detected as an isolated source at energies above 10 keV. Above 30 keV the source becomes background-dominated, and below 10 keV the source is too faint to be detected over thermal emission from the Plume region and Sgr A East, which contribute due to the NuSTAR point spread function (PSF).

4. SPECTRAL ANALYSIS

We extracted source spectra from the three NuSTAR Sgr A* observations using a 20″ radius circular region centered on the Chandra position (white circle in Figure 1). This region is optimal for spectral analysis since it significantly reduces the contribution of the nearby Plume and Sgr A East emission, indicated in Figure 1, and maximizes the signal-to-noise ratio. After rebinning NuSTAR spectra to >20 counts per bin, we performed spectral fitting with XSPEC version 12.8.0 (Arnaud 1996) and adopted the abundance and atomic cross-section data from Wilms et al. (2000) and Verner et al. (1996), respectively. Due to the broad NuSTAR PSF, this source extraction region will also contain thermal emission from the Sgr A East Plume and North regions. The NuSTAR spectrum can therefore be fit with an absorbed thermal and non-thermal model, T&abs*(apec+powerlaw).
NuSTAR background spectra were extracted from partial annuli shown in Figure 1 (green dashed region). These regions were chosen to remove instrument and cosmic X-ray background, as well as the contribution of point sources detected by Chandra (Muno et al. 2003). These sources, which are too faint to be detected by NuSTAR individually, collectively add an additional background component. Muno et al. (2003) used Chandra to resolve these point sources and determined that they were peaked at the Galactic Center and decrease radially from Sgr A* outward. We therefore chose background regions at the same radial distance from Sgr A* as the Cannonball, and avoided the known filaments, Sgr A East and detector chip gaps.

We used data from Chandra ACIS-I to constrain the column density. The Chandra spectrum was obtained from 82 ACIS-I observations, spanning from 2000 October to 2012 October, with a total integration time of 4 Ms. We used a source region \( r = 1.6' \) to remove contamination from the adjacent soft foreground star, CXOOGC J174545.2–285828, which has a thermal spectrum negligible above 2 keV (P05) and does not affect NuSTAR spectra. The Chandra background spectra were extracted from a region adjacent to the Cannonball, in order to subtract thermal emission from the Plume and Sgr A East. The Chandra spectrum can be fit with an absorbed power-law model, \( \text{Tab}^{\text{powerlaw}} \).

We then jointly fit the NuSTAR and Chandra data. The absorption coefficient and the power-law parameters were linked between the two data sets. We analyzed the NuSTAR spectra in 3–30 keV and Chandra data in 2–8 keV. The fit results are shown in Figure 2 and Table 2. The best-fit power-law photon index is \( \Gamma = 1.6 \pm 0.4 \), consistent with the Chandra results of P05. The discrepancy between the best-fit absorption column and that found in P05 is due to our use of more recent absorption and abundance data.

As an alternative approach, we restricted the NuSTAR data to the 13–30 keV band to clearly isolate the non-thermal Cannonball emission from the low-temperature thermal components of the Sgr A East Plume and North regions. We then jointly fit NuSTAR and Chandra spectra with an absorbed power-law model for both spectra, with all parameters linked. The best-fit parameters for the power-law model, shown in Figure 2 and Table 2, are consistent with the values found in the full-band spectral analysis.

5. TIMING ANALYSIS

The high time resolution of NuSTAR allows a search for pulsations down to periods of \( P = 4 \) ms, covering the expected range for a rotation powered pulsar. Previous searches were restricted to \( P > 147 \) ms (P05). We evaluated the power at each frequency (oversampling by a factor of two) using the \( Z_{\nu}^2 \) test statistic for \( n = 1, 2, 3, 5 \), to be sensitive to both broad and narrow pulse profiles. We initially restricted the timing search to photons energies in the 3–25 keV range and used an aperture of 20″ to optimize the signal-to-noise ratio.

From a search of all the observations, the most significant signal was \( Z_{\nu}^2 = 48.61 \) for ObsID 30001002001, corresponding to a probability of false detection of \( \phi = 0.25 \) for \( 28 \times (8.9 \times 10^{28}) \) search trials. The resulting period is not reproduced in the other observations. We repeated our search for an additional combination of energy ranges \( 3 < E < 10 \) keV, \( 10 < E < 25 \) keV and aperture size \( r < 10'' \). We also searched the combined data set in \( (f_n, f_p) \)-space around our best candidates from the individual observations. None of these resulted in a significant detection. We conclude that no pulsed X-ray signal is detected from the Cannonball. After taking into account the estimated background emission (except for PWN contribution) from Section 4, we place an upper limit on the pulse fraction at the 99.73% confidence level (3σ) of \( f_p \leq 43\% \) for a sinusoidal signal in the 3–25 keV band for the \( r < 20'' \) aperture.

![Figure 2](image_url)  
Figure 2. Cannonball joint fit with NuSTAR and Chandra. Left: 2–30 keV joint fit. Solid lines are the best-fit model. Dashed lines are the model components (thermal, and non-thermal) of the NuSTAR data. Right: Cannonball-only spectral fit with an absorbed power-law model. For both images, black indicates NuSTAR FPMA data, red indicates Chandra ACIS data.

### Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Power Law+Apec</th>
<th>Power Law</th>
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</thead>
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<tr>
<td><strong>NuSTAR energy band (keV)</strong></td>
<td>3–30</td>
<td>13–30</td>
</tr>
<tr>
<td>( N_H(10^{22} \text{ cm}^{-2}) )</td>
<td>( 31^{+2}_{-0.3} )</td>
<td>( 32^{+2}_{-2} )</td>
</tr>
<tr>
<td>Power-law index</td>
<td>( 1.6^{+0.3}_{-0.0} )</td>
<td>( 1.6^{+0.4}_{-0.3} )</td>
</tr>
<tr>
<td>( kT ) (keV)</td>
<td>2.8 ± 0.1</td>
<td>( \cdots )</td>
</tr>
<tr>
<td>( \chi^2 ) (dof)</td>
<td>0.81 (66)</td>
<td>0.90 (39)</td>
</tr>
<tr>
<td>( F_{\nu}(2–10 \text{ keV}) )</td>
<td>7 ± 2</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>( F_{\nu}(10–30 \text{ keV}) )</td>
<td>9^{+6}_{-3}</td>
<td>9 ± 1</td>
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</table>

**Notes.** Best-fit parameters of the Cannonball, joint fit NuSTAR and Chandra data. The errors are 90% confidence level. Flux values are obtained from the power-law component, and have units \( 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \).
6. DISCUSSION

6.1. Is the Cannonball a Pulsar?

*NuSTAR* observations of the Cannonball establish the existence of a non-thermal power-law component extending up to \( \sim 30 \) keV. The joint fit to the *NuSTAR–Chandra* spectrum shows a single power law with a photon index of \( \Gamma = 1.6 \) extending from 2 keV to \( \sim 30 \) keV. Furthermore, the >10 keV X-rays are coincident to \( \sim 3\sigma \) with the central point-like head of the cometary structure detected by *Chandra*. This is fully consistent with expectations from a PWN. The highest energy X-rays are associated with the highest energy electrons—the ones which cool most quickly downstream from the termination shock. Given that the soft X-rays detected by *Chandra* are emanating from a region of \( \sim 2\sigma \), one expects the emission above 10 keV to be from an even smaller region. Indeed this is consistent with the *NuSTAR* detection of an unresolved point source, localized on the centroid of the soft X-ray emission.

Thus the cometary soft X-ray morphology and point-like hard X-ray emission are consistent with a bulk velocity field cooled by synchrotron emission—a PWN.

Further support for a PWN origin for the Cannonball comes from the radio observations (ZMG13), where a cometary morphology is also detected, along with an extended plume and tail region consistent with a ram pressure-confined outflow. ZMG13 also point out the similarity of the head–tongue structure with the Mouse PWN. Moreover, the hardening of the radio spectrum downstream from the head–tongue structure is indicative of a cooling outflow downstream from a termination shock.

The non-thermal energy spectrum for the head region of the Cannonball shows a steepening of \( \Delta \alpha = \alpha_e - \alpha_r = 0.9 \pm 0.5 \), with \( \alpha_e = \Gamma - 1 \). This is comparable within uncertainties to the classic case of a 0.5 break in the radio–X-ray spectrum, which is the spectral steepening associated with the continuous injection of electrons into a homogeneous source cooled by synchrotron losses. Further support for the PWN identification comes from the transverse velocity measured by ZMG13. Previous work (Maeda et al. 2002; Sakano et al. 2004; Park et al. 2005) all propose a Type II SN event as a likely origin for Sgr A East, and the \( \sim 500 \) km s\(^{-1}\) transverse velocity is consistent within expectations for Type II SNe, where high pulsar ejection velocities are expected.

Neither radio nor *NuSTAR* searches turn up any pulsation. It is very rare to detect radio pulsars near the Galactic Center due to interstellar dispersion (Deneva et al. 2009). Additionally, the Cannonball sits in a region of high X-ray background making detection of X-ray pulsations difficult. Our pulsar fraction upper limit of 43% indicates that the Cannonball has a spin period shorter than 4 ms or its pulsar emission is buried under the bright PWN emission. Our result extends the range of non-detection from 147 ms (P05) to 4 ms. In several young PWNe (e.g., G21.5–0.9; Nynka et al. 2013), pulsar emission remains undetected in the X-ray band due to significantly brighter PWN emission. Therefore, the non-detection of pulsations from the Cannonball is not surprising.

Some PWN, such as G21.5–0.9, exhibit strong \( \gamma \)-ray emission detectable with HESS (H. E. S. S. Collaboration et al. 2007). Inverse-Compton emission for the Cannonball was predicted using a model by Zhang et al. (2008), incorporating an appropriate IR flux (Hinton & Aharonian 2007). Based on the diffuse \( \gamma \)-ray emission in the Galactic Center (Viana 2011), the Cannonball would either have marginal or no detection by HESS.

### 6.2. Magnetic Field of the Cannonball PWN

An estimate of the PWN magnetic field can be obtained from the *NuSTAR* and *Chandra* data. We assume a constant (mean) magnetic field and a bulk flow velocity field downstream of the termination shock of the form \( v(r) = c/(3r_f/r^2 \), where \( r_f \) is the termination shock radius. These are approximations to the exact solution of Kennel & Coroniti (1984). Integrating this equation we obtain \( r_f(E) = (c^2/\alpha)\tau^{1/3} \). We assume \( r_f \gg r_s \), (the results below confirm). X-ray emission ceases at downstream distance \( r_f(E) \), and \( \tau(E) \) is the timescale for synchrotron cooling of electrons emitting X-rays of characteristic energy \( E \). Normally the termination shock radius is estimated by balancing the pressure of the relativistic wind with the ram pressure of the interstellar medium (ISM) (Gaensler & Slane 2006). However, since the Cannonball moves through the hot plume region of Sgr A East, we add an additional term for the thermal pressure so that \( E/(4\pi r_f^2 c\omega) = \rho v^2 + P_{th} \) where \( E \) is the pulsar spindown power, \( \rho \) the density of the ISM, \( v \) the pulsar space velocity and \( \omega \) a fill factor for the pulsar wind. P05 assume that the Cannonball outflow is energizing the plasma observed in the Plume region. Thus the Plume’s X-ray emitting plasma provides a direct measure of the ISM density, \( n \), through which the Cannonball is moving. From P05 one derives this ISM density for the Plume of \( n \sim 9 \text{ cm}^{-3} f^{-1/2} \), where \( f \) is the plasma volume filling factor. The thermal pressure of the Plume was given in P05, and we convert this to an effective thermal velocity, \( P_{th} = \rho v^2 (v_k = 465 \text{ km s}^{-1}) \). The \( E \) for the pulsar cannot be obtained directly, since no pulsations were detected (Section 5). However, Gotthelf (2003) provides an empirical formula relating \( E \) to the measured photon index, \( \Gamma = 2.36 - 0.021 E_{40}^{-1/2} \). Using the *NuSTAR* derived photon index \( E \) yields \( E = 7 \times 10^{36} \text{ erg s}^{-1} \) (Table 3).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( L_x(2-10 \text{ keV}) ) (erg s(^{-1}))</td>
<td>( 6 \times 10^{33} )</td>
</tr>
<tr>
<td>( L_x(10-30 \text{ keV}) ) (erg s(^{-1}))</td>
<td>( 7 \pm 1 \times 10^{33} )</td>
</tr>
<tr>
<td>( E ) (erg s(^{-1}))</td>
<td>( \sim 7 \times 10^{46} )</td>
</tr>
<tr>
<td>( r_f ) (pc)</td>
<td>( \sim 0.003-0.005 )</td>
</tr>
<tr>
<td>( B(\text{PWN}) ) (( \mu \text{G} ))</td>
<td>( \sim 313-530 )</td>
</tr>
<tr>
<td>( B(\text{NS}) ) (G)</td>
<td>( \sim 5 \times 10^{12} )</td>
</tr>
</tbody>
</table>

#### Notes.
Best-fit parameters of the Cannonball, joint fit with *NuSTAR* and *Chandra* data. The errors are 90% confidence level. Flux values are obtained from the power-law component of the *NuSTAR* data. Line-of-sight distance to the Cannonball is assumed to be 8 kpc.
\[ r_s \sim (0.003-0.005) pc f^{1/4} \omega^{-1/2}, \] consistent with estimates of the termination shock radius for other PWN. The magnetic field is \[ B \sim (313–530) \mu G f^{1/3} \omega^{-2/3}. \] The magnetic field estimate is in excellent agreement with the lower limit of \[ B > 300 \mu G \] obtained by ZMG13 for the Cannonball head assuming energy equipartition.

### 6.3. Magnetic Field of the Putative Pulsar

Assuming a magnetic braking index of 3 and an initial spin period \( P_o \ll P \), where \( P \) is the current spin period, an expression for the NS surface magnetic field strength can be obtained by (very approximately) assuming that the pulsar characteristic age is equal to the observed age \( \tau \):

\[ B = 3.2 \times 10^{19} G (\pi^2 I/\tau^2 \dot{E})^{1/2} \] (Manchester & Taylor 1977). Using the \( \dot{E} \) derived above, a pulsar age of 9000 ± 100 yr, and assuming \( I = 10^{45} g cm^2 \) for a NS of 1.4 \( M_\odot \) and \( R = 10 \) km, we obtain \( B \sim 5 \times 10^{12} G \).

### 7. SUMMARY

The Cannonball has been detected by NuSTAR at energies up to \( \sim 30 \) keV, revealing the presence of non-thermal emission. This observation, combined with the recent discovery of proper motion of the Cannonball with speed \( \sim 500 \) km s\(^{-1} \) and direction pointing toward the center of the Sgr A East SNR, further solidifies the case that the Cannonball is the NS associated with Sgr A East. A timing search for pulsation was unsuccessful. An estimate of the PWN magnetic field from the X-ray data is consistent with a lower limit obtained from radio data by equipartition arguments.

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### REFERENCES


