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\textsubscript{proj} \sim 500 km s\textsuperscript{-1}) pulsar candidate with a cometary pulsar wind nebula (PWN) located \sim 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 1.6 power law, typical of a PWN, and has an X-ray luminosity of L(3–30 keV) = 1.3 \times 10\textsuperscript{34} erg s\textsuperscript{-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 radio 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 in Fe and other elements; a “Plume” region with solar abundances. Each region contains a thermally emitting plasma of temperature \textit{kT} \sim 5–10 keV. Based on the total Fe abundance, several authors conclude that Sgr A East is likely the result of a Type II supernova (SN) explosion (Maeda et al. 2002; Sakano et al. 2004; Park et al. 2005). However, none of the observations conclusively rule out a Type Ia explosion. The presence of a non-thermal radio shell with no corresponding X-ray emission, along with the center-filled X-ray morphology, argue persuasively that Sgr A East is a mixed morphology supernova remnant (SNR; Maeda et al. 2002).

Outside the radio shell of Sgr A East, just north of the Plume, lies the Chandra source CXOGC J174545.5–285829 (Muno et al. 2003), termed “the Cannonball.” This source has faint surrounding asymmetric X-ray emission, slightly elongated in 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 (\sim 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 (\sim 30' \times 15') and a long radio tail (\sim 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 \sim 500\pm 100 km s\textsuperscript{-1}, flat spectrum (\alpha \approx -0.44 \pm 0.08 for the compact head, S_\nu \propto \nu^{-\alpha}) and the cooling linear tail (\alpha \approx -1.94 \pm 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 $10' \times 10'$ 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 (Barri*er 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 $\sim 2''$ 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 were corrected for on-board clock drift and precessed to the solar system barycenter using the JPL-DE200 ephemeris and 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 did not find any elongation of the source within statistical uncertainties. We cannot detect the small $\sim 2''$ tail observed by *Chandra* (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 rebining *NuSTAR* spectra to $\geq 20$ 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).

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Start Date (UTC)</th>
<th>Exposure (ks)</th>
<th>Target</th>
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</thead>
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<td>2012 Jul 20</td>
<td>166.2</td>
<td>Sgr A*</td>
</tr>
<tr>
<td>30001002003</td>
<td>2012 Aug 4</td>
<td>83.8</td>
<td>Sgr A*</td>
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<tr>
<td>30001002004</td>
<td>2012 Oct 16</td>
<td>53.6</td>
<td>Sgr A*</td>
</tr>
<tr>
<td>80002013002</td>
<td>2013 Oct 27</td>
<td>54.1</td>
<td>Magnetar ToO</td>
</tr>
<tr>
<td>80002013004</td>
<td>2013 May 4</td>
<td>42.1</td>
<td>Magnetar ToO</td>
</tr>
<tr>
<td>80002013006</td>
<td>2013 May 11</td>
<td>35.6</td>
<td>Magnetar ToO</td>
</tr>
<tr>
<td>80002013012</td>
<td>2013 Jun 14</td>
<td>29.1</td>
<td>Magnetar ToO</td>
</tr>
</tbody>
</table>

*Note.* The exposure times listed are corrected for good time intervals.

Figure 1. *NuSTAR* mosaic image of the Cannonball, Plume, and Sgr A* region in 3–79 keV band. The Cannonball is indicated by the white circle with radius of 20''. Background regions are indicated by the green dashed regions. *Chandra* 3–8 keV contours are overlaid in black, and approximate positions of the Plume and Sgr A East are in yellow. The image is shown with a linear color scale and the scale range chosen to highlight the Cannonball emission. Inset: *NuSTAR* mosaic image of the Cannonball in 10–30 keV band.
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, CXOOG C174545.2–285828, 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, \( T_{abs}^*\text{powerlaw} \).

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 cleanly 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 \( Z^2 \) 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 \( Z^2 = 48.61 \) for ObsID 30001002001, corresponding to a probability of false detection of \( \phi = 0.25 \) for \( 28 \times (8.9 \times 10^8) \) 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 \((f, \dot{f})\)-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 (3\( \sigma \)) of \( f_p \leq 43\% \) for a sinusoidal signal in the 3–25 keV band for the \( r < 20' \) aperture.
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 ~30 keV. The joint fit to the NuSTAR–Chandra spectrum shows a single power law with a photon index of $\Gamma = 1.6$. Extended from 2 keV to ~30 keV. Furthermore, the >10 keV X-rays are coincident to ~3$^9$ 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 ~2$^9$, 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 exhibits a steepening of $\Delta \alpha = \alpha_x - \alpha_t = 0.9 \pm 0.5$, with $\alpha_t = \Gamma - 1$. 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 ~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 pulsed fraction upper limit of 43% indicates that the Cannonball has a spin period limiting the detection of X-ray pulsations difficult. Our pulsed fraction upper limit of 43% indicates that the Cannonball has a spin period making 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.

### Table 3

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tr>
<td>$L_{\alpha}(2-10 \text{ keV}) \ (\text{erg s}^{-1})$</td>
<td>$6 \times 10^{33}$</td>
</tr>
<tr>
<td>$L_{\alpha}(10-30 \text{ keV}) \ (\text{erg s}^{-1})$</td>
<td>$7 \pm 1 \times 10^{33}$</td>
</tr>
<tr>
<td>$E \ (\text{erg s}^{-1})$</td>
<td>$\sim 7 \times 10^{36}$</td>
</tr>
<tr>
<td>$r_t \ (\text{pc})$</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>$B(\text{NS}) \ (\text{G})$</td>
<td>$\sim 5 	imes 10^{12}$</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.

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 $r_f(E) = (c_0^2/\alpha)^{1/3}$. We assume $r_t \gg r_f$, (which the results below confirm). X-ray emission ceases at downstream distance $r_c(E)$, 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 $E/4\pi r_c^3 \omega = \rho v^2 + P_{\text{th}}$ 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, $P_{\text{th}} = \rho v_{\text{th}}^2/(9h = 465 \text{ km s}^{-1})$. 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, $\Gamma = 2.36 - 0.021 E^{-1/2}$. Using the NuSTAR derived photon index yields $E = 7 \times 10^{36} \text{ erg s}^{-1}$ (Table 3).

With the above estimates the termination shock radius is $r_f = 0.006 \text{ pc}(1+(v/465))^2 f^{-1/2} 1/2 \omega^{-1/2}$, where $v$ is the pulsar space velocity in km s$^{-1}$. Using the cooling timescale, a function of magnetic field strength $B$ and characteristic energy $E$ (Ginzburg & Syrovatskii 1965), one can solve the cooling length scale equation to obtain $B = 884 \mu \text{G}(1 + (v/465)^2)^{2/3} f^{-2/3} \omega^{-1/3}$. The cooling length scale used to derive the magnetic field was estimated from the 3–8 keV Chandra image of P05, assuming the maximum extent of the image was associated with the (slowest cooling) 3 keV X-rays ($r_f = 0.03 \text{ pc}$). The 500 km s$^{-1}$ transverse velocity obtained by ZMG13 is a lower limit on the pulsar space velocity. Approximately 90% of all pulsars have space velocities less than 900 km s$^{-1}$ (Arzoumanian et al. 2002), so using these velocities as an approximate range, one obtains
rs \sim (0.003–0.005) \, \text{pc} \, f^{1/4} \, \omega^{-1/2}, \text{ 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}. \text{ The magnetic field estimate is in excellent agreement with the lower limit of } B \geq 300 \, \mu G \text{ 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 $P_0 \ll P$, 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 $\tau$: $B = 3.2 \times 10^{19} \, \text{G} \, (\pi^2 I/\tau^2 \dot{E})^{1/2}$ (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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