The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
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First results from the *NuSTAR* "mini-survey" of the Galactic center region

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Abstract. One of the major science objectives of the Nuclear Spectroscopic Telescope Array (*NuSTAR*) observatory is to perform the first sub-arcminute, hard X-ray survey of several square degrees of the Galactic plane, centered on a region near the Galactic center. As a prelude to the full survey, which began in July 2013, *NuSTAR* conducted a ~ 500 ks, $0.3 \times 0.4°$ "mini-survey" focused on Sgr A* and its environs. We present analysis of several candidate pulsar wind nebulae and filaments, which are revealed to be intense sources of X-ray emission at > 10 keV.

Keywords. Sgr A*, Cannonball, Sgr A-E, Sgr A East

1. Introduction

The Nuclear Spectroscopic Telescope Array (*NuSTAR*) observatory, launched in June 2012, is the first focusing X-ray telescopes with high effective area above 10 keV and sensitivity over the energy band $3-79$ keV (Harrison *et al.* 2013). Two co-aligned X-ray optics and focal plane modules (FPMA and FPMB) provide angular resolution of $58''$ (half-energy diameter) and $18''$ full width half maximum (FWHM), with characteristic spectral resolution of 400 keV (FWHM) at 10 keV.

One of the main science goals of *NuSTAR* is to conduct a survey of the region around the Galactic center (GC) which overlaps the $2 \times 0.8°$ field previously observed by *Chandra*. This full survey continues sporadically through the spring of 2014. Data from this region were obtained in July and October of 2012 and in April of 2013 as part of campaigns to study flaring in Sgr A*, to study the newly discovered magnetar SGR J1745−29 (Mori *et al.* 2013) and to preliminary study the region just east of Sgr A*. These observations comprise ~ 500 ks of data and are collectively referred to as the "mini-survey."

2. Overview of the mini-survey region

Figure 1 shows an image of the mini-survey region in the $10-40$ keV energy band. The most prominent feature is the supernova remnant (SNR) Sgr A East. This is a broad-band image, but the spectrum shows that the Sgr A East emission extends only up to ~ 20 keV. It is consistent with thermal bremstrahlung (Perez *et. al.* 2013). To the east-southeast of the Sgr A complex lies a series of molecular clouds (MC) that are sources of diffuse hard X-rays. There are also several hard X-ray emitting filaments and point sources located in the MC region. To the southwest of the Sgr A complex is the bright non-thermal radio filament (NTF) Sgr A-E. To the northeast of Sgr A East is the Cannonball, a candidate pulsar wind nebula (PWN).

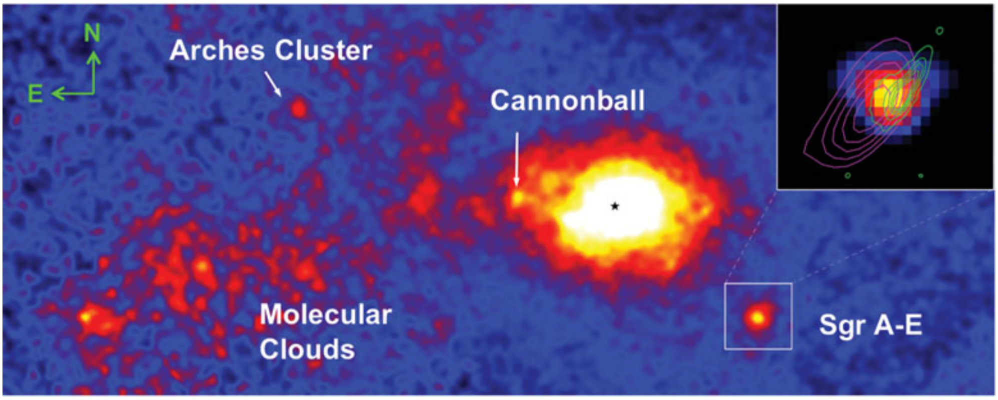

Figure 1. *NuSTAR* view of the central 9′ × 20′ of the Galactic center (10–40 keV). Sgr A* is indicated by a black star. The 40″ × 40″ inset is Sgr A-E overlaid with *Chandra* (green) and radio (magenta) contours. [A COLOR VERSION IS AVAILABLE ONLINE.]

3. The Cannonball

The Cannonball lies just outside the radio shell of Sgr A East. It was first detected by *Chandra* (Muno *et al.* 2003). The source is extended at $2-8$ keV with a head-tail morphology, with the tail pointing towards the center of Sgr A East. Recent radio observations (Zhao, Morris, & Goss 2013; hereafter ZMG13) show a similar morphology to the *Chandra* image. ZMG13 obtained a transverse speed by combining their current radio position with archival radio data. Placing Sgr A East at the GC yields a transverse velocity of $\sim 500\ \mathrm{km\,s^{-1}}$. This velocity, typical of a runaway neutron star (NS), combined with a very flat radio spectrum for the head ($\alpha \sim -0.4$; $S_\nu \propto \nu^{-\alpha}$) and a cooling linear tail ($\alpha \sim -1.94$) suggests the Cannonball is a PWN associated with Sgr A East.

NuSTAR observed the Cannonball for ~ 200 ks in July-November of 2012. The image and spectrum are shown in Figure 1 and 2a respectively (Nynka *et al.* 2013). This hard-band image suppresses most of the intense thermal emission from Sgr A East, making the Cannonball readily visible. The spectrum extends to ~ 30 keV. Spectral parameters were determined by a joint fit to *NuSTAR* and *Chandra* data, using both a thermal component for Sgr A East ($kT = 2.8$ keV) and a power-law component ($\Gamma = 1.6$).

The *NuSTAR* observations clearly establish a non-thermal component, something not previously discernible by *Chandra*. The hard-band X-rays are coincident to the $\sim 3''$ positioning uncertainty with the central point-like head detected in both *Chandra* and radio observations. This is consistent with a ram-pressure dominated PWN with a trail of leptons cooling by synchrotron emission as they are advected beyond the PWN termination shock. The *NuSTAR* image is consistent with a point source. The highest energy X-rays correlate with the highest energy leptons, which cool the fastest. Thus the very high energy *NuSTAR* X-rays are located nearest to the termination shock, which at a fraction of a parsec (Gaensler & Slane 2006) is not resolvable with *NuSTAR*. The break between the radio and X-ray spectrum of ~ 0.5 is consistent with constant injection of electrons into a homogeneous environment (Kennel & Coroniti 1984). The combination of *NuSTAR* and radio observations leave little doubt the Cannonball is a PWN. A search for pulsation in the *NuSTAR* energy band was unsuccessful.

ZMG13 estimated the magnetic field in the head of the Cannonball using the assumption of energy equipartition. They obtained a lower limit to the magnetic field of 300μG. It is an open question whether energy equipartition is generally valid for PWN,

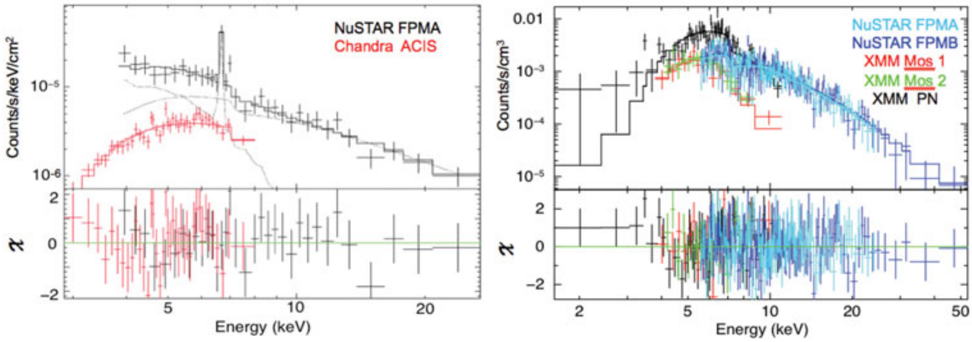

Figure 2. Left: $2-30$ keV *NuSTAR* Cannonball spectra joint fit with *NuSTAR* and *Chandra*. Solid lines are the best-fit model. Dashed lines are the model components (thermal, and non-thermal) of the *NuSTAR* data. **Right:** $2-50$ keV Sgr A-E joint fit with *NuSTAR* and *XMM-Newton* spectra, fit with an absorbed non-thermal power-law model. [A COLOR VERSION IS AVAILABLE ONLINE.]

so it is useful to check this assumption. One can independently determine the B-field from the *NuSTAR*, radio and *Chandra* data. This requires the photon index (*NuSTAR*), the transverse velocity (radio), the temperature of the region around the PWN (*NuSTAR*/*Chandra*) and the maximum spatial extent of the lowest energy X-rays (*Chandra*). The exact procedure is detailed elsewhere (Nynka *et al.* 2013). This radio/X-ray approach yields a measured magnetic field of $B \sim (313-530)\mu$G $f^{1/3}\omega^{-2/3}$ where f is the plasma filling factor in the Cannonball vicinity and ω is the relativistic wind filling factor (Gaensler & Slane 2006). This is in excellent agreement with the lower limit of ZMG13.

4. Non-thermal filaments: Sgr A-E

Sgr A-E is the most luminous non-thermal object detected in the *NuSTAR* band in the mini-survey field. ~ 17 non-thermal filaments in the GC later were first detected as radio sources (e.g. Yusef-Zadeh *et. al.* 1984), and later shown to be strong X-ray sources. The origin of the radio and X-ray emission of these filaments is a subject of active debate. Sgr A-E was discovered in archival *XMM-Newton* and *Chandra* observations (Sakano *et. al.* 2003; Lu *et. al.* 2003).

NuSTAR accrued 338 ks of data on Sgr A-E. A $10-50$ keV *NuSTAR* image of Sgr A-E, overlaid with *Chandra* $2-10$ keV and radio contours is shown in Figure 1. Figure 2b shows the spectrum of Sgr A-E. The X-ray emission extends up to ~ 50 keV. The spectrum is well-fit by a power-law with a photon index of $\Gamma = 2.28$, and is indicative of synchrotron emission. Such high energy X-rays require electrons $\lesssim 100$ TeV, about 3 times higher energy than required to account for the *Chandra* electrons. What is the origin of these electrons?

Several ideas have been put forth (Lu *et al.* 2003, Yusef-Zadeh *et al.* 2005). Previously, a PWN has been suggested. The *NuSTAR* and *Chandra* images suggest that a PWN must be moving to the southeast. The head must be associated with the *NuSTAR* point-like emission, since the most energetic (*NuSTAR*) X-rays come from near the termination shock, nearest the NS. The lower energy (*Chandra*) electrons are advected, and cooling more slowly, leaving a trail behind the PWN. However this picture is not really viable, since the centroid of the radio emission should not lie ahead of the hard X-ray emission. Such a morphology has never been seen in PWN. Another possibility is a SNR shell-MC interaction. The idea is motivated by the claims of a SNR with an extended radio shell interacting with a MC located at the position of Sgr A-E (Ho *et al.* 1985). This hypothesis

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is disfavored because all theories of SNR-MC interactions predict an upwards spectral break in the *NuSTAR* energy band, which is not seen. Moreover the X-ray morphology is not correct, since substantial shell hard X-rays are expected. Also the reality of the SNR is unclear.

A possible explanation is magnetic flux tubes in which energetic electrons have been trapped (Yusef-Zadeh & Morris 1987). A knot of enhanced magnetic field at the position of Sgr A-E is hinted at in the original radio images (Ho *et al.* 1985). This idea is greatly strengthened by more recent high sensitivity radio maps (Morris, private communication and these proceedings), which show a knot of radio emission at Sgr A-E and a filamentary structure extending through Sgr A-E, the nearby Sgr A-F and into the Sgr A complex. The question still remains, from where do the electrons come? There are several likely answers. Cosmic-ray protons produced in supernova explosions can diffuse $\gtrsim$ tens of parsecs to MCs. Proton-MC interaction produces secondary electrons of energy $\gtrsim 100$ TeV that can diffuse freely out of the cloud (Gabici *et al.* 2005). We propose that these electrons are trapped in the enhanced magnetic field of the adjacent flux tubes, producing hard X-rays. Another possible source of electrons is old, low surface brightness PWN. Recently it was suggested (Bamba *et al.* 2010) that older PWN have weaker magnetic fields, allowing electrons to escape and diffuse distances of tens of parsecs in the low magnetic field of the GC. Such electrons can become trapped in magnetic flux tubes and emit synchrotron radiation. These proposed explanations would suggest a correlation between MCs, hard X-ray emitting filaments and knots of radio emission. There is some evidence for such a correlation in filaments being detected by *NuSTAR* in the mini-survey. More details on the Sgr A-E analysis and origin of energetic electrons powering the radio knots to produce hard X-rays can be found in an upcoming paper (Zhang *et. al.* 2013).

5. Summary

Preliminary results of the *NuSTAR* mini-survey have yielded a number of interesting results. The bright, hard X-ray emission of Sgr A East is entirely thermal. The Cannonball is an energetic hard X-ray source, and the *NuSTAR* and radio data show it is almost certainly a runaway PWN associated with Sgr A East. The hypotheses that the Sgr A-E hard X-ray emission is due to the presence of a PWN or a SNR-MC interaction is strongly disfavored. Instead it is potentially an example of a magnetic flux tube powered by primary cosmic-ray electrons from old PWNe or secondary cosmic-ray electrons from proton-MC interactions.

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