Suzaku OBSERVATIONS OF THE DIFFUSE X-RAY EMISSION ACROSS THE FERMI BUBBLES’ EDGES

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ABSTRACT

We present Suzaku X-ray observations along two edge regions of the Fermi Bubbles, with eight ≃ 20 ksec pointings across the northern part of the North Polar Spur (NPS) surrounding the north bubble and six across the southernmost edge of the south bubble. After removing compact X-ray features, diffuse X-ray emission is clearly detected and is well reproduced by a three-component spectral model consisting of unabsorbed thermal emission (temperature $kT \simeq 0.1$ keV) from the Local Bubble (LB), absorbed $kT \simeq 0.3$ keV thermal emission related to the NPS and/or Galactic Halo (GH), and a power-law component at a level consistent with the cosmic X-ray background. The emission measure (EM) of the 0.3 keV plasma decreases by ≃ 50% toward the inner regions of the north-east bubble, with no accompanying temperature change. However, such a jump in the EM is not clearly seen in the south bubble data. While it is unclear if the NPS originates from a nearby supernova remnant or is related to previous activity within/around the Galactic Center, our Suzaku observations provide evidence suggestive of the latter scenario. In the latter framework, the presence of a large amount of neutral matter absorbing the X-ray emission as well as the existence of the $kT \simeq 0.3$ keV gas can be naturally interpreted as a weak shock driven by the bubbles’ expansion in the surrounding medium, with velocity $v_{\text{exp}} \sim 300$ km s$^{-1}$ (corresponding to shock Mach number $M \simeq 1.5$), compressing the GH gas to form the NPS feature. We also derived an upper limit for any non-thermal X-ray emission component associated with the bubbles and demonstrate, that in agreement with the findings above, the non-thermal pressure and energy estimated from a one-zone leptonic model of its broad-band spectrum, are in rough equilibrium with that of the surrounding thermal plasma.

Subject headings: acceleration of particles — cosmic rays — Galaxy: center — Galaxy: halo — X-rays: ISM

1. INTRODUCTION

The Large Area Telescope (LAT; Atwood et al. 2009) onboard the Fermi satellite is a successor to EGRET onboard the Compton Gamma-ray Observatory (Hartman et al. 1999), with much improved sensitivity and resolution over a broader energy range. Along with the GeV detections of various $\gamma$-ray source types (e.g., Nolan et al. 2012), yet another important LAT discovery concerns the large-scale $\gamma$-ray structure, the so-called “Fermi Bubbles,” extending for about 50$^\circ$ (or 8.5 kpc) above and below the Galactic Center (GC), with a longitudinal width $\sim 40^\circ$ (Dobler et al. 2010, Su et al. 2010). It has been suggested that these bubbles have relatively sharp edges and are symmetric with respect to the Galactic plane and the minor axis of the Galactic disk. The $\gamma$-ray emission associated with the bubbles is characterized by a hard spectrum with the differential $\gamma$-ray spectral photon index $\Gamma \simeq 2$

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no significant spectral or total intensity variations have been found within the structure, with the exception of some hints for an additional substructure consisting of a cocoon and jet-like features extending in the north-west and south-east directions (Su & Finkbeiner 2012). The sharp edges may suggest the presence of a shock at the bubbles’ boundaries. If however this is the case, and if the shock is the sole acceleration site of the $\gamma$-ray emitting particles, both the observed flat intensity profile and the uniformly hard spectrum within the bubbles’ interior extending for about 10 kpc, seem rather difficult to explain.

Importantly, the $\gamma$-ray emission of the bubbles is spatially correlated with the flat-spectrum microwave excess known as the “WMAP haze.” The haze, recently confirmed with Planck observations (Planck Collaboration et al. 2013), is characterized by a spherical morphology with a radius $\sim 4$ kpc centered at the GC, and is visible up to at least $|b| \simeq 30^\circ$ (Finkbeiner 2004, Dobler & Finkbeiner 2008). The entire microwave continuum of the haze is consistent with a power-law distribution with spectral index $\alpha = 0.5$, and is best interpreted as synchrotron emission from a flat-spectrum population of cosmic ray (CR) electrons. Hence it has been argued that the WMAP haze and the Fermi bubbles are linked, and that the $\gamma$-ray emission of the bubbles is simply the inverse-Compton scattering of the cosmic microwave background (IC/CMB) emission from the same electron population producing the observed microwave synchrotron excess (e.g., Su et al. 2010, Mertsch & Sarkar 2011). In this model, the smaller latitudinal extension of the WMAP haze may be due to a decrease in the magnetic field intensity with increasing latitude. However, the expected polarization of the
haze was not detected in the most recent accumulation of the WMAP-7 year data (Gold et al. 2011), indicating that the magnetic field in the bubbles is heavily tangled, or an alternative emission mechanism is at work. In this context, some authors argued that the bubbles/haze structure may be explained as rather being due to a population of relic CR protons and heavier ions injected about $\approx 10^{10}$ Gyr years ago during the outburst of a high areal density star-forming activity around the GC (Crocker & Aharonian 2011).

At X-ray frequencies, the ROSAT all-sky survey (RASS) provides full-sky images with FWHM $12'$ at photon energies in the $0.5 - 2$ keV range (Snowden et al. 1995). Hints of signatures of the entire north bubble structure can be noted in the ROSAT map (e.g., Fig. 1 in Wang 2002; Fig. 6 in Bland-Hawthorn & Cohen 2003; also, Figs. 18 & 19 in Su et al. 2010). Particularly noteworthy is a prominent Galactic feature called the North Polar Spur (NPS) seen in the $0.75$ keV ($R_{45}$ band) map, a large region of enhanced soft X-ray emission projected above the plane of the Galaxy which coincides with a part of the radio Loop I structure. Sofue (2000, and references therein) interpreted the NPS as a large-scale outflow from the GC with a corresponding total energy of $\sim 10^{55} - 10^{56}$ erg released on a timescale of $\sim 10^{7}$ yr. This idea was questioned by several authors who argued that the NPS and the rest of the Loop I may instead be a nearby supernova remnant (Berkhuijsen et al. 1971) or may be related to the wind activity of the Scorpio-Centaurus OB association located at a distance of 170 pc (Egger & Aschenbach 1995). While the GC scenario seems more plausible in view of the recent discovery of the Fermi bubbles (Su et al. 2010), the distance and origin of the NPS is still under debate, and we discuss this issue in more depth in this paper (Section 4.2).

Motivated by the substantial observational and theoretical progress recently made toward understanding the nature and origin of the large-scale structures extending above and below the GC regions, particularly with the discovery of the Fermi Bubbles, we conducted Suzaku X-ray observations of high-Galactic latitude regions ($43^\circ < |b| < 54^\circ$) positioned across the north-east and the southern-most edges of the bubbles. In Section 2, we describe the details of the Suzaku observations and data reduction procedures. The results of the analysis are given in Section 3, including the detailed spectral modeling and images obtained within the $0.4 - 10$ keV range. Here we concentrated on the analysis of the diffuse emission and assumed all the relatively bright compact X-ray features detected at $\geq 5$σ level are most likely background active galactic nuclei (AGN) or galaxies unrelated to the Galactic Halo (GH) and/or the NPS. Some information regarding
these compact X-ray features are provided in the Appendix, along with the details of our further investigation concerning the data analysis. In Section 4 we summarize our findings and discuss the expansion of the bubbles and their interaction with the GH gas. We compared the obtained Suzaku results with RASS observations, thus providing guidance for future high-sensitivity all-sky X-ray studies with instruments like MAXI (Matsuoka et al. 2009) or eROSITA (Merloni et al. 2012). We also revisit the widely debated issue concerning the origin of and the distance to the NPS. We argue that the NPS is formed by plasma which has been compressed and heated by a weak shock driven in the GH environment by the expanding bubbles. Finally, we discuss the energy and pressure balance between the thermal and non-thermal plasma components within the regions of interest by means of modeling the spectral energy distribution (SED) of the bubbles and of the surrounding medium as probed with the Suzaku data. Throughout, unless otherwise noted, all statistical uncertainties reported in the paper are at the 1σ level.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Suzaku Observations

We conducted Suzaku observations of the north-east and southern edges of the Fermi Bubbles as a part of an AO7 program in 2012 with a total (requested) duration of 280 ks. The campaign consisted of 14 observations, ~ 20 ksec each, consisting of eight pointings overlapping with the north-east bubble edge and across part of the NPS, with the remaining six pointings over the southern edge of the south bubble. Table 1 summarizes the times of the exposures, directions of the pointing centers (in both equatorial and Galactic coordinates), and the effective duration of each pointing. The angular offset between each pointing was 1.02 deg for the north-east edge and 0.88 deg for the south bubble edge. Because of the overlap with the NPS, we obtained additional pointings in the northern bubble region (spacing them out more widely) than in the southern bubble in order to sample a wider angular range.

The Suzaku satellite (Mitsuda et al. 2007) carries four sets of X-ray telescopes (XRT; Serlemitsos et al. 2007), each with a focal-plane X-ray CCD camera (X-ray Imaging Spectrometer, XIS; Koyama et al. 2007) sensitive to photons in the energy range of 0.3 – 12 keV. Despite the relatively large point spread function (PSF) of the XRT, with a half-power diameter of ~ 2.0′, Suzaku is the ideal instrument for the intended study because it provides a low and stable Non X-ray Background (NXB), particularly suitable for investigating extended and low surface-brightness X-ray sources (Mitsuda et al. 2007; Tawa et al. 2008). Three spectrometers (XIS 0, 2, 3) have front-illuminated (FI) CCDs, while the XIS 1 utilizes a back-illuminated (BI) CCD. Each XIS covers a 18′ × 18′ region on the sky. Because of an anomaly in 2006 November, the operation of the XIS 2 was terminated, thus here we use only the remaining three CCDs. The cameras were operated in the normal full-frame clocking mode with the 3 × 3 or 5 × 5 editing mode. Although Suzaku carries also a hard X-ray detector (HXD; Takahashi et al. 2007), hereafter we do not use the data collected by its PIN and GSO instruments.

The screening was http://www.astro.isas.jaxa.jp/suzaku/analysis

| ID | start time (UT in 2012) | stop time (UT in 2012) | R.A. [°] | DEC [°] | l [°] | b [°] | Exposure [ksec] |
|---|---|---|---|---|---|---|---|
| N1 | Aug 08 10:23 | Aug 08 23:03 | 233.401 | 9.076 | 15.480 | 47.114 | 20.0 |
| N2 | Aug 07 23:41 | Aug 08 10:22 | 233.623 | 8.079 | 14.388 | 47.011 | 18.3 |
| N3 | Aug 07 10:31 | Aug 07 23:40 | 233.834 | 7.087 | 13.321 | 46.308 | 20.4 |
| N4 | Aug 06 23:20 | Aug 07 10:30 | 234.034 | 6.098 | 12.280 | 45.606 | 19.0 |
| N5 | Aug 05 23:04 | Aug 06 09:33 | 234.250 | 5.090 | 11.255 | 44.871 | 17.2 |
| N6 | Aug 06 09:34 | Aug 06 23:18 | 234.405 | 4.131 | 10.263 | 44.204 | 22.0 |
| N7 | Aug 08 23:06 | Aug 09 10:20 | 234.551 | 3.174 | 9.291 | 43.537 | 19.4 |
| N8 | Aug 09 10:21 | Aug 09 23:53 | 234.713 | 2.200 | 8.334 | 42.838 | 13.5 |

Table 1: Suzaku Observation Log

Note. — a: Right ascension of Suzaku pointing center in J2000 equinox.
b: Declination of Suzaku pointing center in J2000 equinox.
c: Galactic longitude of Suzaku pointing center.
d: Galactic latitude of Suzaku pointing center.
e: Suzaku XIS exposure in ksec.
based on the following criteria: (1) only ASCA-grade 0, 2, 3, 4, 6 events were accumulated with hot and flickering pixels removed from the XIS image using the CLEAN SIS script (Day et al. 1998); (2) the time interval after the passage of the South Atlantic Anomaly (T_SAA_HXD) greater than 500 s; (3) targets were located at least 5° and 20° above the rim of the Earth (ELV) during night and day, respectively. In addition, we also selected the data with a cutoff rigidity (COR) larger than 6 GV. After this screening, the sum of the net exposures for good time intervals was 149.8 ks for the N1−N8 and 105.7 ks for the S1−S6 pointings (see Table 1). In the reduction and the analysis of the Suzaku XIS data, the HEADAS software version 6.12 and the calibration databases (CALDB) released on 2012 July 11 were used, all kindly provided by the XIS instrumental team. The XIS cleaned event dataset was obtained in the combined $3 \times 3$ and $5 \times 5$ edit modes using XSELECT.

We extracted the XIS images from only the two FI CCDs
FIG. 3.—As in figure 2, but for the southern bubble Suzaku fields S1–S6.

(XIS 0, XIS 3) because the BI CCD (XIS1) has lower imaging quality due to its higher instrumental background. The XIS images were made within three photon energy ranges of $0.4 - 10\text{keV}$, $0.4 - 2\text{keV}$, and $2 - 10\text{keV}$. In the image analysis, we excluded calibration sources at the corners of the CCD chips. The images of the NXB were obtained from the night Earth data using XISNXBGEN (Tawa et al. 2008). Since the exposure times for the original data were different from that of the NXB, we calculated the appropriate exposure-corrected original and NXB maps using XISEXPMAPGEN (Ishisaki et al. 2007). The corrected NXB images were next subtracted from the corrected original images. In addition, we simulated flat sky images using XISSIM (Ishisaki et al. 2007) and applied a vignetting correction. All the images obtained with XIS0 and XIS3 were combined. Throughout the reduction process, we also performed vignetting correction for all the XIS images described in Section 3. Finally, the images were smoothed with a Gaussian function with $\sigma = 0.07'$ (Gaussian kernel radius set as 8 in DS9).

With the combined XIS0+3 images, we first ran the source detection algorithm in XIMAGE to discriminate compact X-ray features from intrinsically diffuse X-ray emission. This is a well established approach as described in Giommi et al. (1992) and detailed in NASA’s HEASARC Software page for background calculation examples. In summary, the process was composed of three steps. First, using the BACKGROUND command, we estimated the background by dividing an image into equal boxes characterized by the typical PSF size, and rejecting those not complying with certain statistical criteria. The average in the remaining boxes was taken as the background value. Second, with the EXCESS command, a sliding-cell method was used to find areas with excesses over the background threshold (typically, $>3-5\sigma$). Finally, in the third step performed with the SEARCH command, we merged the excess cells into source boxes using the Suzaku PSF and vignetting to estimate source significances and statistics. Here we set the box sizes as $1.1' \times 1.1'$ (corresponding to $64 \times 64$ pixels) or $0.5' \times 0.5'$ (corresponding to $32 \times 32$ pixels) for crowded fields because of the blurring due to the Suzaku XIS PSF, and the detection threshold at $3\sigma$. We performed the source detection separately in the $0.4 - 10\text{keV}$, $0.4 - 2\text{keV}$, and $2 - 10\text{keV}$ ranges, and concatenated the results.

For the spectral analysis, we used all the FI and BI CCDs, namely, XIS0, 1, 3 to maximize the photon statistics. For the bright compact X-ray features described above, we set the source regions to within $1' - 2'$ circles centered on the emission peaks, and estimated the backgrounds from annuli on the corresponding CCD chips with inner and outer radii of $2'$ and $4'$, respectively. The response (RMF) and auxiliary (ARF) files were produced using the analysis tools XISRMFGEN and XISSIMARFGEN (Ishisaki et al. 2007), which are included in the software package HEAsoft version 6.12. For the analysis of the diffuse emission, we considered the bands, but these were faint sources marginally detected below the $5\sigma$ level. The list and derived spectra of the bright compact emitters thus detected (all at approximately $>5\sigma$), which are not associated with catalogued sources, are summarized in Appendix A.

A few spots were seen only in the $0.4 - 2\text{keV}$ or $2 - 10\text{keV}$ bands, but these were faint sources marginally detected below the $5\sigma$ level. The list and derived spectra of the bright compact emitters thus detected (all at approximately $>5\sigma$), which are not associated with catalogued sources, are summarized in Appendix A.
tire CCD chip as a source region, but only after removing all the compact features detected above the 3σ level, with typical 2′ radius circles (see Appendix A and Tables 3 & 4). The ARF files were produced assuming that the diffuse emission is distributed uniformly within circular regions with 20′ radii (giving the ARF area of 0.35 deg²) using XISSIMARFGEN and new contamination files (released on July 11, 2012). In contrast to the point source analysis, we did not subtract background photons from the region in the same CCD chip but instead modeled the is the isotropic background continuum (see Section 3.2.2 for details).

We note that even though the most recent version of XISSIMARFGEN reproduces well the degradation of the CCD quantum efficiency below 2 keV due to contamination, significant differences in the spectral shape of the measured emission continua between XIS0, 1, and 3 were found below ≳ 0.5 keV. Therefore we did not use the spectral data below 0.6 keV for XIS 0 and 3, and below 0.4 keV for XIS 1. We also did not use the high energy data above 8 keV for XIS 1 due to low photon statistics. Light curves were also constructed for bright X-ray compact features, none of which indicated any significant variability within the short exposures performed.

3. RESULTS
3.1. X-ray Images

The obtained 0.4 – 10 keV XIS images (combined XIS0 and 3) are shown in Figure 2 for the north-east field (N1–N8; from top-left to bottom-right), and in Figure 3 for the southern field (S1–S6; from top-left to bottom-right). At first glance, one can note some difference between the different pointings in the north, such that the surface brightness of the targeted regions gradually decreases across the bubble’s edge toward the GC from the outermost (N1) to the innermost (N8) pointings. On the other hand, this trend is not as clear in the south (from S1 to S6). In the figures, magenta crosses mark the positions of compact X-ray features detected at ≥ 5σ level which are likely associated with catalogued background sources from the NED or SIMBAD database. The other X-ray features detected with Suzaku at high significances, which are missing any obvious Galactic or extragalactic identifications, are denoted as “src1-11” in the north, and “src1-10” in the south. A few bright features seen in the images but not listed here are spurious sources arising from instrumental artifacts (e.g., near the corners of the CCD chips). Red circles or ellipses in Figures 2 and 3 indicate the source extraction regions for the unassociated compact X-ray emitters.

With the given photon statistics and the relatively large PSF of the XIS, it is impossible to determine if the detected compact features are point-like, or if they are (marginally) extended. In this context, it is important to estimate the number of background AGN likely to be found within each XIS field of view (FOV). Following Stawarz et al. [2013], who utilized the results of the Chandra Deep Field-South observations (Fozzi et al. [2001]), one should expect the number of AGN with 0.5 – 2 keV or 2 – 10 keV fluxes > 5 × 10⁻¹⁴ erg cm⁻² s⁻¹ to be ~ 40/deg² at most. This implies two or three uncatalogued AGN within each XIS FoV, which is close to the number of detected compact X-ray features without any obvious optical identification. In order to elaborate more on the possible AGN associations, we have investigated the available mid-infrared (MIR) maps of the areas covered by our Suzaku exposures using the NASA Widefield Infrared Survey Explorer (WISE; Wright et al. [2010]) satellite data. The all-sky WISE data release was searched for sources present within radii of 1.5″ around the positions of the region centers listed in the Appendix A and no infrared counterparts were found.

3.2. X-ray Spectra
3.2.1. Compact X-ray Features

We first fitted the spectra of all the unassociated compact X-ray features detected at significance levels above ≥ 5σ using XSPEC (see Table 5). Within the given photon statistics, the X-ray spectra were all well represented by single power-law models moderated by the Galactic absorption, with the exception of src2 in the N1 field which required a substantial excess absorption in the neutral hydrogen column density $N_{H} = 6.9^{+6.2}_{-3.4} \times 10^{22}$ cm⁻² with respect to the Galactic value of $N_{H, \text{Gal}} = 3.37 \times 10^{20}$ cm⁻². While the nature of this source is unclear, considering only one such source detected in all the Suzaku fields, it could be a background type-II AGN where the soft X-ray emission is heavily obscured by thick surrounding material (e.g., Krumpe et al. [2008]). The results of the spectral fitting for these uncatalogued X-ray emitters are tabulated in Appendix A. Because of the large spread in their fitted spectral parameters – unabsorbed 2–10 keV fluxes with a range $(0.1 – 7.5) \times 10^{-13}$ erg cm⁻² s⁻¹ and photon spectral indices $\Gamma$ ranging from 0.8 to 3.1 – it is difficult to draw robust conclusions on the nature of the compact X-ray sources. Nevertheless, the number density of the detected X-ray spots (two at most per individual XIS FoV) is comparable to that expected for background AGN as noted above (Section 3.1). Moreover, there is no systematic difference in the number of point-like sources detected in different fields at different distances from the GC. This again suggests that the compact X-ray features are most likely unrelated to the diffuse GH/NPS structure, but are rather background objects.

3.2.2. Diffuse Emission

As detailed in Section 2.2, we considered the entire CCD chip as a source region for the analysis of the diffuse emission after removing all the compact features detected above 3σ significances, regardless of whether they were catalogued or uncatalogued X-ray sources (see Appendix A and Tables 3 & 4). The spectra of the Suzaku pointings were all fitted with a three component model $\text{APEC1 + WABS}^\ast (\text{APEC2 + PL})$. The model includes an unabsorbed thermal component (denoted as $\text{APEC1}$) representing the Local Bubble (LB) emission and/or contamination from the Solar-Wind Charge Exchange (SWCX; Fujimoto et al. [2007]), an absorbed thermal component (denoted as $\text{APEC2}$) representing the GH or NPS, and an absorbed power-law component (denoted as $\text{PL}$) corresponding to the isotropic CXB radiation. As for the absorbed diffuse emission, the neutral hydrogen column density was fixed to the Galactic value $N_{H, \text{Gal}}$ in the direction of each pointing (see Table 2), while the photon index for the CXB component was fixed at $\Gamma_{\text{CXB}} = 1.41$ (Kushino et al. [2002]). In the cases where $N_{H}$ was left free in the spectral fitting, we also list the ratio of the absorbing column density to the full Galactic column, $N_{H}/N_{H, \text{Gal}}$ (Table 2). Note that within the statistical errors, most of the values are either consistent with unity, or even larger than unity (for N2, N5 and N7). However, due to the relatively low photon statistics in the southern pointings, we can provide only upper limits hence the re-

\[^2\]http://heasarc.gsfc.nasa.gov/docs/astroe/prop_tools_suzaku.html
TABLE 2
FITTING PARAMETERS FOR THE diffuse EMISSION COMPONENT

| ID | \(N_{\text{HI, Gal}}^{\text{North Bubble}} \times 10^{20} \text{ cm}^{-2}\) | \(N_{\text{HI, Gal}}^{\text{South Bubble}}\) | \(kT_1\) \((10^{-2} \text{ cm}^{-6} \text{ pc})\) | \(\chi_1^2\) | \(kT_2\) \((10^{-2} \text{ cm}^{-6} \text{ pc})\) | \(\chi_2^2\) | \(\text{CXB Norm}\) | \(\chi^2/\text{dof}\) |
|----|-----------------|-----------------|-----------------|-----|-----------------|-----|-------------|--------|
| North Bubble | | | | | | | | |
| N1 | 3.37 | 0.8-3.8 | 0.1(fix) | 3.47±0.38 | 0.299±0.012 | 5.49±0.38 | 3.34±0.04 | 1.07/144 |
| N2 | 3.83 | 2.9-5.5 | 0.1(fix) | 3.26±0.45 | 0.315±0.012 | 5.38±0.36 | 3.03±0.04 | 1.38/162 |
| N3 | 3.86 | 0.8-4.1 | 0.1(fix) | 4.09±0.71 | 0.319±0.015 | 5.28±0.50 | 1.08±0.05 | 1.07/96 |
| N4 | 4.06 | 0.8-2.9 | 0.1(fix) | 4.58±0.49 | 0.324±0.014 | 5.11±0.37 | 0.71±0.04 | 1.35/135 |
| N5 | 4.26 | 1.1-4.8 | 0.1(fix) | 3.16±0.44 | 0.285±0.009 | 5.40±0.36 | 0.94±0.03 | 1.19/148 |
| N6 | 4.45 | 0.6-4.0 | 0.1(fix) | 4.66±0.43 | 0.316±0.015 | 3.82±0.51 | 1.08±0.03 | 1.20/166 |
| N7 | 4.76 | 4.4-6.7 | 0.1(fix) | 3.83±0.40 | 0.290±0.010 | 4.56±0.52 | 0.64±0.03 | 1.25/153 |
| N8 | 5.02 | 1.0-5.1 | 0.1(fix) | 4.43±0.53 | 0.315±0.018 | 3.28±0.58 | 0.78±0.03 | 1.08/106 |

| South Bubble | | | | | | | | |
| S1 | 1.84 | < 1.8 | 0.1(fix) | 3.01±0.64 | 0.283±0.063 | 0.93±0.27 | 1.02±0.05 | 1.03/88 |
| S2 | 1.66 | < 2.6 | 0.1(fix) | 3.03±0.55 | 0.369±0.064 | 0.80±0.28 | 0.97±0.04 | 1.15/71 |
| S3 | 1.89 | < 4.1 | 0.1(fix) | 1.97±0.63 | 0.270±0.039 | 1.48±0.20 | 1.02±0.05 | 1.49/62 |
| S4 | 2.16 | < 2.6 | 0.1(fix) | 2.59±0.61 | 0.260±0.043 | 1.37±0.37 | 1.11±0.04 | 1.15/100 |
| S5 | 2.45 | < 0.9 | 0.1(fix) | 3.02±0.44 | 0.262±0.036 | 1.15±0.30 | 0.92±0.03 | 1.22/117 |
| S6 | 3.03 | < 4.4 | 0.1(fix) | 4.06±0.71 | 0.325±0.051 | 1.18±0.39 | 0.79±0.05 | 1.22/117 |

Note: a: The absorption column densities for the CXB and the GH/NPS components \((\text{WABS+APEC} + \text{PL})\) components were fixed to Galactic values in Dickey & Lockman (1990).

b: The ratio of the absorbing column density to the full Galactic column along the line of sight when \(N_{\text{HI}}\) was left free in the spectral fitting.

c: Temperature of the LB/SW/CXB plasma fitted with the APEC model for the fixed abundance \(Z = Z_{\odot}\).

d: Emission measure of the LB/SW/CXB plasma fitted with the APEC model for the fixed abundance \(Z = Z_{\odot}\).

e: Temperature of the GH/NPS plasma fitted with the APEC model for the fixed abundance \(Z = Z_{\odot}\).

f: Emission measure of the GH/NPS plasma fitted with the APEC model for the fixed abundance \(Z = Z_{\odot}\).

g: The normalization of the CXB in units of \(5.85 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\), given in Kushino et al. (2003) as an average of 91 observation fields, assuming a power-law model with a photon index \(\Gamma_{\text{CXB}} = 1.4\).
Fig. 4.— The XIS spectra of the diffuse emission component for the N1–N8 pointings, together with the best fit model curves (APEC1+WABS*(APEC2+PL)) and residuals. The LB component ($kT \approx 0.1$ keV; APEC1) dominates the lowest 0.4–0.6 keV range, thermal emission related to the NPS and/or Galactic halo ($kT \approx 0.3$ keV; APEC2) dominates the 0.6–1.5 keV range, and a power-law component from the CXB dominates above 1.5 keV ($\Gamma \approx 1.4$; PL). XIS 0 data/fits are shown in black, XIS 1 in red, and XIS 3 in green.
Fig. 5.— As in figure 4, but for the S1—S6 pointings.

gle from the expected boundary of the bubble’s edge (following Su et al. 2010). Interestingly, the EM of the $kT \simeq 0.3$ keV component appears to change significantly and abruptly (by about $\simeq 50\%$) around the north-east edge (i.e., between pointings N6 and N7). The constant fit to the EM profile resulted in a $\chi^2$ value of 37.6 for 7 degree of freedom with a corresponding probability, $P(\chi^2) \leq 10^{-5}$. Note the probability increased significantly to $P(\chi^2) = 0.96$ if we fit the EM between N1 and N5 only ($\chi^2 = 0.61$ for 4 degrees of freedom). This change is not due to any artifact in the spectral fitting, e.g., an increased amount of contamination from the LB/SWXC component as we checked in careful detail (Appendix C), although there still remains a possibility that we are seeing local X-ray features such as clumps or filaments within the NPS rather than an EM change physically associated with the north-east bubble edge. The analogous “jump” in the EM is not as clear in the southern bubble edge, and this could be partly explained in this case because we have only one FOV (S1) just outside the edge. But as we argue below (Section 4.1), since the ROSAT 0.75 keV map can be considered as a good tracer of the GH/NPS component, the absence of any NPS-like feature south from the GC may suggest that no sharp boundary is present there. Also note that the temperature of the APEC2 component is almost constant in both the north-east and southern fields. This temperature is a bit higher than the canonical value of the GH, $kT \simeq 0.2$ keV, derived for Galactic longitudes $65^\circ < l < 295^\circ$ (Yoshino et al. 2009) or $120^\circ < l < 240^\circ$ (Henley et al. 2010) to avoid contamination from the GC region. Very recent measurements of the Galactic halo’s X-ray emission using 110 XMM observations also confirm its temperature is fairly uniform (median = 0.19 keV, interquartile range = 0.05 keV; Henley & Shelton 2013).
4. DISCUSSION

4.1. Comparison with RASS Maps

In section 3.2.2, we showed that the diffuse X-ray emission, after removing compact X-ray sources and features detected at $\geq 3\sigma$ level, is generally well reproduced by the three component plasma model: (1) $kT \simeq 0.1$ keV emission due to the LB with some contamination from SWCX, (2) $kT \simeq 0.3$ keV plasma related to the GH and/or NPS gas, and (3) $\Gamma \simeq 1.4$ power-law as expected from the CXB. Particularly noteworthy is that the EM of the GH/NPS component gradually drops by $\simeq 50\%$ around the expected boundary of the north-east Fermi Bubble edge. This drop is consistent with a visual impression from both ROSAT all sky survey R45 (0.75 keV) and R67 (1.5 keV) maps, indicating that the X-ray surface intensity gradually decreases from the N1 to N8 fields (see Fig. 1 top-left), away from the NPS. However, the ROSAT maps alone are not sufficient to quantify the observed changes in the plasma parameters, simply because we are dealing with a multi-temperature convolution of various emission components and ROSAT images do not provide the necessary detailed spectral information.

In order to investigate this issue in more detail, in Figure 7 (top panel) we present the observed ROSAT (R45) counting rate at 0.75 keV, as a function of the EM (for the APEC2 component strictly), which we obtained from the N1–N8 and S1–S6 pointings, along with the EM values of the GH/NPS components measured at the NPS center at low Galactic latitudes in the previously reported Suzaku and XMM observations (see Figure 1; Willingale et al. 2003; Miller et al. 2008). The horizontal error bars in the figure correspond to $1\sigma$ statistical errors for the EM values estimated from the spectral model fits of the Suzaku (or XMM) data (see Table 2), while the minimum and maximum counting rates in the ROSAT map (Snowden et al. 1995, 1997) are given to indicate approximately the fluctuations present in the ROSAT data centered on the same observing region (e.g., Yoshino et al. 2009). Considering the angular resolution $\sim 0.2^\circ$ of the ROSAT maps (Snowden et al. 1997), we estimated the source counts within circles with radius $\sim 0.2^\circ$. Here we do not exclude contributions from point features in the ROSAT maps, since even though bright X-ray sources were in the regions of interest. In fact, we confirmed that the sum of the X-ray fluxes from the Suzaku (Section 3.2.1) constitute less than 5% of the diffuse emission in the 0.5–2 keV energy range. Also the contribution of unresolved sources in the 1–2 keV band measured by ROSAT is $4.4\times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$ (Hasinger et al. 1993; Tozzi et al. 2001), which again corresponds to $\sim 5\%$ of the diffuse emission in the 0.5–2 keV energy range. However, we remark that even sources situated well outside the Suzaku field of view ($17^\prime \times 17^\prime$) may contribute significantly to the reported ROSAT counting rates, hence contamination from background sources may be more significant than approximated above. Figure 7 (bottom panel) presents the analogous counting rates measured at 1.5 keV (R67 band).

As shown in Figure 7, the R45 counting rates appear overall to track the EM of the GH/NPS component surprisingly well with a correlation factor 0.97$\pm$0.01. However, inspecting the data from the Suzaku pointings of the north-east (N1–N8) and south (S1–S6) regions in more detail suggests the correlation does not hold well within these observations. This could be due to local (but small) variations in the thermal plasma parameters (e.g., abundance; see Appendix C), different contributions from the contaminating sources especially in the ROSAT maps, and fluctuations of the CXB intensity (although this spectral component contributes negligibly to the R45 bandpass). The contribution and superposition of such background sources is predominantly negligible for the previous NPS pointings because they pointed at much brighter parts of the NPS at low Galactic latitude. Even with such complications, it appears the R45 map data can still serve as a useful overall tracer of the distribution of the GH gas even though the ROSAT maps carry no explicit spectral information. In contrast, in the R67 map (1.5 keV) the contribution from the CXB becomes significant, diluting any intrinsic correlation between the 1.5 keV counting rate and the EM of the GH/NPS component (correlation factor reduced to 0.86$\pm$0.02). In this band, additional fluctuations in the ROSAT counting rates above 1 keV could be expected due to an increased amount of background sources like AGN due to the poorer resolution of these data with respect to that of Suzaku.

The correlation between the ROSAT R45 counting rate and the $kT \simeq 0.3$ keV plasma EM derived from the Suzaku observations may suggest that the X-ray spectra around the north-
east and southern Fermi Bubbles resemble each other, even though the giant NPS structure is seen only in the north. Indeed, what we found is that the diffuse X-ray emission around the bubbles both above and below the GC, is well characterized by the three-component model introduced above, with similar values of the fitted model parameters. The same holds for the previously X-ray targeted fields of the bright center of the NPS analyzed in Willingale et al. (2003) and Miller et al. (2008). Note that in these previous works, the GH emission was assumed to be composed of an absorbed $kT \approx 0.1 \text{ keV}$ component superimposed on the $kT \approx 0.26 \text{ keV}$ continuum attributed to the NPS, and distinct from the GH emission. Although this observational fact could be a chance coincidence and we cannot rule out the possibility that all the emission is simply from the local structure, it appears as likely that the $kT \lesssim 0.3 \text{ keV}$ temperature gas seen at the position of the Fermi Bubbles, including the NPS structure, is of the same GH origin.

4.2. NPS: Shock-Heated Galactic Halo Gas?

Previously, it was widely agreed that the NPS and the rest of the Loop I structure arises from a recent supernova shock wave heating the outer shell of the superbubble, at a distance of about $100 \text{ pc}$ from the Sun (Berkhuijsen et al. 1971; Egger & Aschenbach 1995). Only recently, after the discovery of the Fermi Bubbles in particular, has the alternative interpretation stating that the NPS is a remnant of a starburst or a nuclear outburst which happened near/within the GC about $15 \text{ Myr}$ ago (Sofue 1977, 1984, 1994, 2000, 2003; Bland-Hawthorn & Cohen 2003) entered back into the limelight. The argument against the GC scenario followed from the measurement of the interstellar polarization at a distance of about $100 \text{ pc}$, which seems to trace some part of Loop I including the NPS (Bingham 1967; Mathewson & Ford 1970). However, the observed stellar polarization orientation is almost perpendicular to the direction of the NPS, especially at low Galactic latitudes, which is at odds with the SNR association (e.g., Furst & Reich 1990; Xu et al. 2007; Xiao et al. 2008). Specifically, the NPS radio ridge at $l = 20 - 30^\circ$ runs at angle $130^\circ$ (from GC toward $l = 90^\circ$; Sofue & Reich 1979), while the optical polarization is at $40 - 60^\circ$ (Mathewson & Ford 1970). Thus, the implied local magnetic field orientation is nearly perpendicular to the NPS and does not support the local SNR origin. It has also been argued that the observed optical polarization is aligned with HI filaments of the Hydra ridge, which is a local HI region inflated by magnetic fields, and unrelated to non-thermal features like the NPS (Sofue 1973, 1976). The Hydra HI ridge at $b = 20 - 30^\circ$ also runs at $20 - 50^\circ$, nearly perpendicular to the NPS. Note that HI at $b = 70 - 90^\circ$ appears parallel to the NPS orientation, and that has been taken as evidence for the HI–NPS association. However, as mentioned above, the brightest part of the NPS at $b = 20 - 30^\circ$ is perpendicular to HI. For further details of these arguments, see the discussion in Sofue et al. (1974).

One should note further that both the Suzaku and XMM observations targeting any part of the NPS implied relatively large values of the neutral hydrogen column density $N_H$ absorbing the NPS thermal spectrum in all cases. For example, based on the XMM data, Willingale et al. (2003) derived column densities $0.9$, $0.6$, and $0.5$ times the Galactic value $N_{H, \text{ Gal}}$ for the three different regions positioned at $(l, b) = (25.0^\circ, 20.0^\circ)$, $(20.0^\circ, 30.0^\circ)$, $(20.0^\circ, 40.0^\circ)$, respectively (see Figure 1 for the XMM pointing positions). Similarly, Miller et al. (2008) concluded from spectral fitting of Suzaku data on the brightest part of the NPS, $(l, b) = (26.84^\circ, 21.96^\circ)$, was either $> 0.71$ or $> 0.97$ times the Galactic value, depending on the choice of background regions. At first glance, such high levels of $N_H$ (i.e., column densities more than $0.5$ times the total Galactic value toward in the line-of-sight direction), confirmed by our analysis of the newly acquired Suzaku data, seems to conflict with the idea that the NPS is a local phenomenon. Willingale et al. (2003) mention that the halo and NPS components lie behind at least $50\%$ of the line-of-sight cold gas for which the total Galactic column density in the range $(2 - 8) \times 10^{20} \text{ cm}^{-2}$, and attribute this high $N_H$ to the cold gas distribution in the wall located at $15 - 60 \text{ pc}$. However, the presence of such a wall between the LB and NPS is not confirmed, but was rather an assumption made in order to not conflict with their local model. Miller et al. (2008) also reported high levels of $N_H$ but no discussion about the origin of such large amount of cold gas; throughout, they assumed that the NPS is a local structure based on the interstellar polarization feature and the HI features, both of which cannot however be taken to strongly support the local interpretation as we discuss above.

Moreover, the inspection of the ROSAT maps indicates that the X-ray emission from the NPS is heavily absorbed at $1.5 \text{ keV}$ at low Galactic latitudes (e.g., Snowden et al. 1995), i.e., from the Galactic plane up to $b \approx 10^\circ$. This requires hydrogen column densities as large as $\gtrsim 5 \times 10^{21} \text{ cm}^{-2}$. Meanwhile, any accumulation of neutral gas within a $100 \text{ pc}$ distance by an expanding shock wave should amount to no more than $N_H \approx 3 \times 10^{20} \text{ cm}^{-2}$. Therefore, it seems reasonable and natural to consider the $kT \approx 0.3 \text{ keV}$ plasma component detected in our Suzaku observations of the north-east and southern Fermi Bubbles’ edges is essentially the same as the plasma component seen in the previous observations of the NPS, having the similar temperature, $kT \approx 0.3 \text{ keV}$. Yet it is difficult to conclude if the NPS is physically associated with the GH, because as already emphasized above, the derived temperature of this component is slightly higher than the “canoncial” $kT \approx 0.2 \text{ keV}$ value claimed for the GH gas (Yao & Wang 2005; Yao et al. 2009, 2010; Yoshino et al. 2009; Henley et al. 2010; Henley & Shelton 2013). On the other hand, this discrepancy can be explained as a signature of gas heating by the expanding bubble structure, which drives a low-Mach number shock in the surrounding medium (for a high-Mach number case see, Guo & Mathews 2012; Guo et al. 2012). We return to this issue in Sections 4.3 and 4.4.

Finally, let us comment in this context on the aforementioned jump in the EM of the hot gas component at the north-east bubble edge. Here we propose that the observed $50\%$ decrease in EM is likely due to projection effects related to a cavity inflated by an expanding bubble in the GH environment. Namely, assuming that the Fermi Bubbles are indeed characterized by sharp edges and are symmetric with respect to the observer’s line of sight, a shell of the evacuated gas is expected to form an envelope around the expanding structure. A projection of the emission of this shell onto the bubbles’ interior should then result in the same temperature plasma component (here $kT \approx 0.3 \text{ keV}$) being observed from both within and around the bubbles even if they are devoid of any thermal component, but only with the enhanced emissivity just outside the bubbles’ edges. To estimate the exact shape of the EM profile requires detailed modeling of the emissivity profile as proposed to model the radial profile of shell-type supernova remnants (e.g., Berezhko & Völk 2004).
which is beyond the scope of this paper. Instead, we consider a simple 2-dimensional toy model in which the uniform gas is confined in a donut region between $R_{in}$ and $R_{out}$, where $R_{in} \approx 4 \text{kpc}$ is the radius of the bubble and the observed EM is simply proportional to the path length of gas along the line of sight. Within such a toy model, a 50% drop of EM can be explained if the width of the outer shell of the bubble, $R_{out} - R_{in} \approx 2 \text{kpc}$, i.e., is twice smaller than the bubble radius.

### 4.3. Thermal vs Non-thermal Plasma

In the spectral fitting of the newly acquired Suzaku data, we did not detect any excess non-thermal emission associated with the bubbles, at least at the level exceeding the expected $\sim 10\%$ fluctuations in the CXB. Figure 8 shows the SED of the Fermi Bubbles, from radio to GeV $\gamma$-ray, with the corresponding X-ray upper limit. The GeV data points correspond to the emission of the entire bubbles' structure following Su et al. (2010). The radio data points correspond to the WMAP haze emission averaged over $b = -20^\circ$ to $-30^\circ$, for $|l| < 10^\circ$. The bow-tie centered on the 23 GHz K-band indicates the range of synchrotron spectral indices allowed for the WMAP haze following Dobler & Finkbeiner (2008). In our modeling, we assumed a simple one-zone leptonic model in which the radio emission and GeV $\gamma$-ray emission arise from the same population of relativistic electrons through the synchrotron and inverse-Compton (IC/CMB) processes, respectively (e.g., Su et al. 2010). We are aware that detailed modeling requires also the IC contributions from the dust and starlight, i.e., far infrared and optical/UV backgrounds as detailed in Mertsch & Sarkar (2011). However, such starlight/dust emission at the position of the lobes is anisotropic and non-uniform, therefore special care must be taken when including these additional sources of seed photons. The interstellar stellar radiation field has energy density of $\sim 1 \text{ eV cm}^{-3}$, comparable to that of the CMB, but its contribution is more significant closer to the disk and as such, the conclusion is not significantly affected at high galactic latitudes. In fact, Mertsch & Sarkar (2011, Fig. 2 therein) demonstrated that the IC/CMB contribution is most significant up to 10 GeV in the Fermi-LAT data.

For the electron energy distribution we assume a standard broken power-law form $N_e(\gamma) = N_0 \gamma^{-s - 1}(1 + \gamma/\gamma_{brk})^{-\gamma_{brk} - 1}$, with the injection index $s = 2.2$, and the minimum and maximum electron Lorentz factors set to $\gamma_{min} = 2000$ and $\gamma_{max} = 10^8$, respectively. The parameter $\gamma_{brk} = 10^6$ is the characteristic energy above which the electron spectrum breaks by $\Delta s = 1$. We further anticipate the magnetic field intensity $B = 12 \mu \text{G}$ within the bubbles, and the emission volume $V = 2 \pi R^3$ with radius $R = 1.2 \times 10^{22} \text{ cm}$. The modeling results, shown in Figure 8 as a blue curve, yield the non-thermal bubbles' pressure $p_{n/th} = (U_e + U_B)/3 \approx 2 \times 10^{-12} \text{dyn cm}^{-2}$, where the electron and magnetic field energy densities are $U_e = \int d\gamma n_e c^2 \gamma N_e(\gamma)$ and $U_B = \mu_0 B^2/8\pi$, and the total non-thermal energy stored in electrons and magnetic field $E_{n/th} = (U_e + U_B) \times V \approx 10^{36} \text{ erg}$. The results of our model fitting suggest $U_B \gg U_e$. Note that the derived $B = 12 \mu \text{G}$ seems a factor of $2-4$ higher than the typical magnetic field in our Galaxy, but consistent with independent estimates in the literature of $B = 15 \mu \text{G}$ (Mertsch & Sarkar 2011) or $B = 5-10 \mu \text{G}$ (Su et al. 2010). Following Mertsch & Sarkar (2011), this could be due to an overestimate of microwave flux caused by inappropriate template subtraction. In fact, the model prediction assuming $B = 4 \mu \text{G}$ suggests an order of magnitude smaller flux for the WMAP haze so more detailed modeling of the SED will be justified only after updated Planck and Fermi-LAT measurements are made available. Similarly at this stage, we can neither support or rule out various other models including the hadronic model we mentioned in the introduction section (Crocker & Aharonian 2011). Therefore, our IC/CMB model should be considered as one possible interpretation that should be clarified and tested in the near future.

For comparison, we can also estimate the thermal pressure of the NPS gas as $p_{th} \approx n_g kT$, where $n_g$ is the gas number density and $kT$ is the gas temperature. From our Suzaku observations we take $kT \approx 0.3 \text{ keV}$, and estimate $n_g = (\text{EM}/d)^{1/2}$, where $d$ is the scale length of the X-ray plasma with the given emission measure EM. Assuming the thickness of a thermal X-ray envelope/shell (see the discussion in Section 4.2) as $d \approx 2 \text{kpc}$, we obtain $p_{th} \approx 2 \times 10^{-12} \text{ dyn cm}^{-2}$ and $E_{th} \approx 10^{36} \text{ erg}$. Even though all
these estimates are rough, and are based on clearly over-simplified modeling, they indicate robustly that under all the model assumptions specified above, the non-thermal plasma filling the Fermi Bubbles and the thermal plasma of the bubbles’ immediate surroundings are in pressure and energy equipartition. This finding is in accord with the idea that the NPS feature is composed of the GH gas heated by a shock wave driven by the expanding bubbles. Indeed, in such a situation, pressure equilibrium between shock downstream fluids is expected.

In the framework of the above interpretation, the Mach number of a shock following from the observed temperature ratio $kT_+/kT_- \approx 0.3$ keV/0.2 keV is $M \approx 1.5$, assuming the adiabatic parameter of the GH gas $\gamma = 5/3$. This further implies the upstream (unperturbed GH gas) pressure $p_- \approx 0.8 \times 10^{-12}$ dyn cm$^{-2}$, and the shock velocity $v_{sh} \approx M \times c_{s-} \approx 320$ km s$^{-1}$ for the upstream sound speed $c_{s-} \approx 200$ km s$^{-1}$. As discussed below, the estimated value of $v_{sh}$ is in agreement with the expected expansion velocity of the Fermi Bubbles.

4.4. On the Formation of the Fermi Bubbles

Let us comment here on the formation of the Fermi Bubbles in the context of the presented Suzaku observations. Note again that the discussion below is our speculation based on an assumption that both the Fermi Bubbles and NPS are connected with the GC past activity. Therefore as we have shown above, the local bubble scenario for the NPS can also work in some sense and still leaves a lot of room to be clarified in future works. Nevertheless, there are a number of observations discussed in the literature taken as evidence that the GC has undergone multiple past epochs of enhanced activity on different timescales, due either to AGN-like outbursts or episodes of circumnuclear starbursts. The strongest case among these is the Fe Kα echo from molecular clouds situated a few hundreds parsec apart around Sgr A* (Koyama et al. 1996, Murakami et al. 2000, 2001). Recently, a diffuse clump in an over-ionized state with a jet-like structure has also been found in the Suzaku data for the GC south, ~200 pc from Sgr A*, suggesting a plasma ejection from Sgr A* which happened about a million years ago (Nakashima et al. 2013, in prep.). Outflows of this kind are expected to lead to the formation of bubbles/lobes expanding within the Galactic halo, just like the GC scenario of NPS as well as the Fermi Bubbles, sweeping up the interstellar/halo gas in analogy with the extended lobes seen in distant radio galaxies (Sofue 2000). Totani (2000) has shown that the Fe Kα echo, NPS, and the observed 511 keV line emission toward the GC can be explained naturally in a standard framework of a radiatively inefficient accretion flow (RIAF) in the GC black hole, if the typical accretion rate was about 1,000 times higher than the current rate in the past 10 Myr. The outflow energy expected by such an accretion rate is expected to be $10^{56}$ erg (or $3 \times 10^{41}$ erg s$^{-1}$).

The GH is thought to be rather isothermal, characterized by a temperature, $kT \approx 0.2$ keV, with only some density gradients towards the GC (Yoshino et al. 2009, Henley et al. 2010, Henley & Shelton 2013). During the evolution of the outflow, the evacuated halo gas can be heated, if the bubbles’ expansion is supersonic, due to formation of a shock wave at the edges of the structure. In the previous section we estimated the Mach number of a shock needed to heat the

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**Fig. 8.** SED of the Fermi Bubbles fitted with the one-zone leptonic model (blue curve). We assumed the magnetic field intensity $B = 12 \mu$G within the bubbles, and the emission volume $V = 2 \times 4 \pi R^2$ with radius $R = 1.2 \times 10^{22}$ cm. Full details are given in Section 4.3. The GeV data points correspond to the emission of the entire bubbles’ structure, following Su et al. (2010). The radio data points corresponds to the WMAP haze emission averaged over $b = -20°$ to $-30°$, for $|l| < 10°$. The bow-tie centered on the 23 GHz $K$-band indicates the range of synchrotron spectral indices allowed for the WMAP haze, following Dobler & Finkbeiner (2008). Red dashed line denotes the observed CXB level, and the solid line indicates the Suzaku upper limit for the bubbles’ non-thermal X-ray emission, $\lesssim 9.3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the 2–10 keV energy range, corresponding to $\lesssim 15\%$ of the CXB level.
GH gas from \(kT \simeq 0.2\) keV up to \(kT \simeq 0.3\) keV characterizing the NPS emission as \(\mathcal{M} \simeq 1.5\), corresponding essentially to the trans-sonic expansion velocity of the Fermi Bubbles \(v_{\text{exp}} \sim 300\) km s\(^{-1}\). Interestingly, this is comparable to the escape velocity from the Galaxy. If we assume the velocity is approximately constant during the entire evolution, the characteristic timescale for the formation of the observed structure is \(t_{\text{exp}} \sim R/v_{\text{exp}} \simeq 10\) Myr, where \(R \simeq 4\) kpc is the radius of the bubbles. With the total non-thermal energy estimated above, \(E_{\text{n/th}} \simeq 10^{56}\) erg, the required time-averaged jet/outflow kinetic luminosity then reads as \(L_{\text{jet}} \simeq E_{\text{n/th}}/t_{\text{exp}} \simeq 3 \times 10^{41}\) erg s\(^{-1}\), which is \(~ 0.1\%\) of the Eddington luminosity of the Sgr A* Eddington supermassive black hole. Note that these results are exactly consistent with the independent estimate by \(\text{Totani} \ (2003)\) as described above.

The above estimates are quite modest, and in our opinion, do not conflict with the existing observations. Yet, our arguments are not sufficiently strong to rule out the alternative conventional idea that the NPS originates from a nearby supernova remnant. Worth remarking in this respect is that the expansion velocity we derived conflicts with the order-of-magnitude higher values advocated in the literature (Guo & Mathews, 2012; Guo et al., 2012; Zubovas & Nayakshin, 2012; Yang et al., 2012; Lacki, 2013). We note that such large expansion velocities would result in the formation of a very strong bow shock at the bubbles’ edges, manifesting in very hot gas at the edges of the observed structure with temperatures of \(\gtrsim 30\) keV, absorbing the X-ray emission of the structure, as well as for a power-law component at the level expected from the cosmic X-ray background. We did not find a non-thermal X-ray emission component associated with the bubbles exceeding \(~ 15\%\) fluctuation of the CXB intensity, corresponding to \(< 9.3 \times 10^{-19}\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) in the 2–10 keV energy range. Based on the gathered data, we argued that the North Polar Spur is possibly related to the bubbles rather than being a local phenomenon. This followed from the indirect evidence we found for the presence of a large amount of neutral matter absorbing the X-ray emission of the structure, as well as for a weak shock driven by the bubbles’ expansion in the surrounding medium and compressing the halo gas to form the NPS feature. In this scenario, we estimated the expansion velocity of the bubbles as \(v_{\text{exp}} \sim 300\) km s\(^{-1}\), corresponding to the shock Mach number \(\mathcal{M} \simeq 1.5\). We also showed that the non-thermal pressure and energy estimated by means of modeling the broad-band spectrum of the bubbles in the framework of a simple one-zone leptonic model, \(p_{\text{n/th}} \simeq 2 \times 10^{-12}\) dyne cm\(^{-2}\) and \(E_{\text{n/th}} \simeq 10^{56}\) erg, respectively, are in a rough equilibrium with the pressure and energy of the thermal plasma surrounding the bubble.

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## Appendix

### X-Ray Spectra of Compact Sources

As discussed in the text (Section 3.2.1), we believe that the bulk of the uncatalogued point-like X-ray features detected in our \textit{Suzaku} observations at the \(\gtrsim 5\sigma\) level are background AGN or galaxies and are unrelated to the GH or NPS structure. In this Appendix, we first summarize the positions and the statistical significances of compact X-ray features detected above \(3\sigma\), and possible association of catalogued sources when possible (Tables 3 & 4). X-ray spectral fits of uncatalogued sources detected above \(\gtrsim 5\sigma\) level (with the assumed absorbed power-law model) are then summarized in Table 5.

### Abundance of the \(kT \simeq 0.3\) keV Plasma Component

The limited photon statistics preclude us from precisely determining the metallicity of the absorbed \(kT \simeq 0.3\) keV diffuse emission component, hence we fixed \(Z = 0.2\) Z\(_{\odot}\) in the model fitting (see Section 3.2.2). To validate our assumption, in Figure 9 we plot the temperature \(kT\) versus the abundance for the N1–N8 pointings, derived when both \(Z\) and \(kT\) were allowed to vary. The derived values cluster in a relatively narrow range of \(kT \simeq 0.3\) keV and \(Z \simeq 0.2\) Z\(_{\odot}\) indeed. We note the related discussion...
in Willingale et al. (2003) and Miller et al. (2008) concerning the brightest regions of the NPS targeted by Suzaku and XMM, suggesting the depleted C, O, Ne, Mg and Fe abundances of less than 0.5 \( Z_\odot \), but an enhanced N abundance which was however not clearly seen in our data.

Since the XIS is only sensitive to photon energies above 0.4 keV, clearly distinguishing between the two diffuse thermal components (\( kT \approx 0.1 \) keV due to the LB/SWCX and \( kT \approx 0.3 \) keV due to the GH/NPS) is in general not easy. Therefore, it is in principle possible that a gradual jump visible in the derived EM between different neighboring fields (as seen in Figure 6), may be due to a sudden increase in the amount of contamination from the LB/SWCX component rather than a drop in the GH/NPS component. In order to investigate this issue in more detail, in Figure 10 we plot the variation of the EM of the \( kT = 0.1 \) keV plasma for the N1−N8 and S1−S6 pointings. As expected, no significant variations in the EM are observed, thus confirming the reality of a gradual drop in the EM for the \( kT \approx 0.3 \) keV component claimed in Section 3.2.2.

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Fig. 10.—Variation in the spectral fitted EM parameter of the APEC emission component in the north-east (top) and south (bottom) Suzaku observations, as a function of the angular separation from the bubble edge. No significant changes in the EM at the expected position of the bubbles’ boundary (green dotted line following Su et al. 2010) are seen, consistent with the expectation that the $kT \approx 0.1$ keV plasma component is due to the Local Bubble emission contaminated by the solar wind charge exchange.

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TABLE 3
LIST OF COMPACT X-RAY FEATURES DETECTED ABOVE 3σ LEVEL AND REMOVED IN THE ANALYSIS OF DUFFUSE X-RAY EMISSION: BUBBLE NORTH

| ID | R.A. [°] | DEC [°] | stat siga (σ) | associationb | commentc |
|----|----------|---------|---------------|--------------|-----------|
| src1 | 233.354 | 9.033 | 10.6 | — | — |
| src2 | 233.286 | 9.159 | 9.1 | — | — |
| src3 | 233.304 | 9.098 | 3.7 | — | — |
| src4 | 233.503 | 9.015 | 4.5 | — | — |
| src5 | 233.692 | 8.032 | 4.9 | — | — |
| src6 | 233.825 | 7.110 | 4.9 | — | — |
| src7 | 233.933 | 7.175 | 6.2 | — | — |
| src8 | 233.870 | 7.108 | 3.8 | — | — |
| src9 | 233.779 | 7.032 | 4.1 | — | — |
| src10 | 233.710 | 7.057 | 4.5 | — | — |
| src11 | 233.940 | 7.053 | 3.7 | — | low-E |
| src12 | 233.879 | 7.024 | 7.7 | Radio Source | — |
| src13 | 233.888 | 6.976 | 16.5 | QSO | — |
| src14 | 233.773 | 7.129 | 12.0 | QSO | — |
| src15 | 233.745 | 7.137 | 4.3 | Radio Source | — |
| src16 | 234.102 | 6.160 | 6.7 | Radio Source | — |
| src17 | 234.001 | 6.120 | 5.7 | Galaxy | — |
| src18 | 234.100 | 6.101 | 3.3 | Galaxy | — |
| src19 | 234.018 | 6.150 | 4.4 | Galaxy | — |
| src20 | 234.018 | 6.150 | 4.4 | Galaxy | — |
| src21 | 233.982 | 6.145 | 4.0 | Galaxy | — |
| src22 | 234.000 | 6.195 | 3.5 | Galaxy | — |
| src23 | 234.262 | 5.151 | 3.7 | Galaxy | — |
| src24 | 234.323 | 5.182 | 4.5 | — | — |
| src25 | 234.285 | 5.191 | 4.1 | — | — |
| src26 | 234.420 | 4.170 | 5.4 | — | — |
| src27 | 234.446 | 4.120 | 6.2 | — | — |
| src28 | 234.287 | 4.218 | 3.3 | — | low-E |
| src29 | 234.378 | 4.147 | 7.8 | QSO | — |
| src30 | 234.481 | 3.210 | 5.8 | QSO | — |
| src31 | 234.478 | 3.252 | 3.3 | QSO | — |
| src32 | 234.725 | 2.243 | 5.3 | QSO | — |
| src33 | 234.837 | 2.149 | 20.2 | QSO | — |
| src34 | 234.617 | 2.123 | 15.3 | QSO | — |

NOTE: — a: Statistical significance determined by the source detection algorithm in XIMAGE. Only XIS0+3 data were used since the XIS1 has lower imaging quality due to higher instrumental background.

b: Catalogue association of the source, if available.
c: Sources detected only in the 0.5−2 keV energy range are denoted as “low-E”, and sources detected only in the 2−10 keV energy range are denoted as “high-E”.


TABLE 4
LIST OF COMPACT X-RAY FEATURES DETECTED ABOVE 3σ LEVEL AND REMOVED IN THE ANALYSIS OF DUFFUSE X-RAY EMISSION: BUBBLE SOUTH

| ID  | R.A. [°] | DEC [°] | stat sig [σ] | association | comment |
|-----|---------|---------|--------------|-------------|---------|
| src1 | 332.660 | -45.883 | 4.8 | | |
| src2 | 332.705 | -45.902 | 5.8 | | |
| src3 | 332.649 | -45.758 | 13.7 | Galaxy Group | |
| src4 | 332.723 | -45.947 | 6.9 | QSO | |
| src5 | 331.432 | -45.662 | 4.8 | | |
| src6 | 331.509 | -45.664 | 3.8 | Star | |
| src7 | 330.338 | -45.613 | 8.3 | | |
| src8 | 330.124 | -45.483 | 6.9 | | |
| src9 | 330.225 | -45.423 | 4.0 | | |
| src10 | 330.227 | -45.550 | 3.4 | | |
| src11 | 330.169 | -45.395 | 7.1 | | |
| src12 | 330.096 | -45.337 | 4.5 | Galaxy | |
| src13 | 329.041 | -45.507 | 10.6 | Radio Source | |
| src14 | 329.096 | -45.337 | 4.8 | Star | |
| src15 | 327.788 | -45.245 | 6.6 | | |
| src16 | 327.863 | -45.330 | 3.6 | | |
| src17 | 329.041 | -45.507 | 10.6 | Radio Source | |
| src18 | 327.863 | -45.330 | 3.6 | | |
| src19 | 326.688 | -45.191 | 3.4 | | |
| src20 | 326.496 | -45.106 | 7.0 | Radio Source | |

NOTE. — As in Table 4, but for the sources in the south bubble observations.

TABLE 5
FITTING PARAMETERS FOR COMPACT X-RAY FEATURES DETECTED ABOVE ≥ 5σ LEVEL

| ID  | N_H [10^{20} cm^{-2}] | PL index | PL flux [10^{-14} erg cm^{-2} s^{-1}] | χ^2/dof |
|-----|------------------------|----------|-------------------------------------|---------|
| Bubble North |
| src1 | 3.37 (fix) | 2.44 ± 0.22 | 6.19 ± 1.46 | 1.29/41 |
| src2 | 685 ± 0.340 | 0.76 ± 0.69 | 74.7 ± 21.2 | 1.47/31 |
| src3 | 3.83 (fix) | 2.41 ± 0.36 | 3.96 ± 1.83 | 1.00/67 |
| src4 | 3.86 (fix) | 2.26 ± 0.38 | 2.05 ± 0.82 | 0.79/17 |
| src5 | 3.86 (fix) | 3.06 ± 0.71 | 0.94 ± 0.59 | 1.00/22 |
| src6 | 4.06 (fix) | 1.43 ± 0.33 | 8.35 ± 2.61 | 1.27/17 |
| src7 | 4.06 (fix) | 2.06 ± 0.32 | 3.22 ± 1.92 | 1.30/25 |
| src8 | 4.45 (fix) | 1.67 ± 0.37 | 4.23 ± 1.49 | 1.07/23 |
| src9 | 4.45 (fix) | 2.70 ± 0.45 | 1.43 ± 0.67 | 1.06/28 |
| src10 | 4.26 (fix) | 1.75 ± 0.30 | 5.68 ± 1.79 | 0.36/13 |
| src11 | 5.02 (fix) | 1.40 ± 0.41 | 5.59 ± 2.11 | 1.19/10 |

| Bubble South |
| src1 | 1.84 (fix) | 1.72 ± 0.41 | 3.82 ± 1.98 | 0.94/19 |
| src2 | 1.84 (fix) | 1.34 ± 0.53 | 4.75 ± 2.49 | 0.25/9 |
| src3 | 1.66 (fix) | 1.83 ± 0.49 | 3.17 ± 1.91 | 0.65/13 |
| src4 | 1.89 (fix) | 1.85 ± 0.36 | 7.50 ± 2.60 | 0.96/18 |
| src5 | 1.89 (fix) | 0.93 ± 0.47 | 15.1 ± 3.4 | 0.72/19 |
| src6 | 2.16 (fix) | 2.31 ± 0.14 | 17.2 ± 3.1 | 0.98/68 |
| src7 | 2.16 (fix) | 1.24 ± 0.13 | 8.66 ± 2.79 | 0.98/34 |
| src8 | 2.45 (fix) | 1.60 ± 0.29 | 6.42 ± 1.85 | 1.12/19 |
| src9 | 3.03 (fix) | 1.95 ± 0.65 | 2.56 ± 2.03 | 0.88/7 |
| src10 | 3.03 (fix) | 1.60 ± 0.48 | 8.88 ± 4.27 | 0.78/7 |

NOTE. — a: Absorption column density fixed at the Galactic values, except for src2 in the North, which required an additional column density well exceeding N_H, Gal.
b: Spectral photon index in the single power-law model.
c: Unabsorbed 2 − 10 keV flux.