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Paradigm shift in understanding the Galactic eROSITA Bubbles

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The magnificent bubbles at the Galactic center provide a great channel to understand the effects of feedback on galaxy evolution. The newly discovered eROSITA bubbles show enhanced X-ray emission from the shells around bubbles. Previous works *assumed* that the X-ray emitting gas in the shells has a single temperature component and that they trace the shock-heated lower-temperature Galactic halo gas. Here we show that the thermal structure of the eROSITA bubble shells is more complex. Using Suzaku observations we find with high confidence that the X-ray emission from the shells is best described by a two-temperature thermal model, one near Galaxy’s virial temperature at $kT \approx 0.2$ keV and the other at super-virial temperatures ranging between $kT = 0.4 - 1.1$ keV. Furthermore, we show that temperatures of the virial and super-virial components are similar in the shells and in the ambient medium, although the emission measures are significantly higher in the shells. We argue that the X-ray bright eROSITA bubble shells are the signature of compressed isothermal radiative shocks. The age of the bubbles is constrained to 70–130 Myr. This expansion timescale, as well as the observed non-solar Ne/O and Mg/O ratios, favor the stellar feedback models for the formation of the Galactic bubbles, settling a long-standing debate on the origin of the Galactic bubbles.

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The first all-sky survey performed by the *eROSITA* X-ray telescope¹ has revealed a large hourglass-shaped structure in the center of the Milky-way (MW; [1]), called the *eROSITA bubbles*. The X-ray bright quasi-circular feature in the northern sky, which include structures such as the North Polar Spur and the Loop-I, have been known since their discovery by ROSAT [2]. The new *eROSITA* map shows X-ray emission from a similarly huge quasi-circular annular structure in the southern sky; together they seem to form giant Galactic X-ray bubbles emerging from the Galactic Center (GC).

The large-scale X-ray emission observed by *eROSITA* in its medium energy band (0.6 – 1.0 keV) shows that the intrinsic size of the bubbles is several kiloparsecs across [1]. The *eROSITA bubbles* show striking morphological similarities to the well-known *Fermi bubbles* detected in γ -ray by the *Fermi* telescope [3], but they are larger and more energetic. The *Fermi* and *eROSITA* bubbles (collectively we called the ‘Galactic bubbles’) provide an exciting laboratory for studying the feedback because of their size and the location in the Galaxy. These bubbles are magnificent structures injecting energy/momentum into the MW circum-galactic medium (CGM)² or halo. In order to understand the feedback process, it is important to determine the thermal, kinetic, and dynamical structure of these bubbles.

The Galactic bubbles are expanding into the MW halo; we therefore examine the spatial distribution of the X-ray emission from the bubble shells and from the halo around them to constrain their thermal structure. We conducted a survey of *Suzaku* observations with this goal. We selected 230 archival *Suzaku* observations of the soft diffuse X-ray background (SDXB) to characterize the X-ray emission from the Galactic bubbles (Galactic longitudes $300^\circ < l < 60^\circ$) and from the surrounding extended halo ($60^\circ < l < 300^\circ$).

In order to extract the Galactic bubbles/halo emission from the SDXB, it is crucial to accurately model the other components of the SDXB, such as the Local Bubble (LB), solar wind charge exchange (SWCX), the cosmic X-ray background (CXB), and the instrumental background. We included emission from these components in the spectral fitting (see methods). Spectral fits to the *Suzaku* spectra show that the X-ray emission of the bubble shells as well as the outer halo is best described by two-thermal components, a warm-hot phase near the Galaxy’s virial temperature $kT \approx 0.2$ keV (2.3×10^6 K) and a hot phase at super-virial temperatures ranging between $kT = 0.4 - 1.1$ keV ($0.5 - 1.3 \times 10^7$ K). The best fit models also require overabundance of nitrogen (N/O) in the warm-hot phase, both from and around the bubbles. Toward a few Galactic bubble sightlines, the best fit model also requires super-solar abundance ratios of neon and/or magnesium to oxygen (Ne/O and Mg/O). Fig. 1 shows the X-ray emission maps of the warm-hot and the hot components of the Galactic bubbles and the surrounding halo emission.

The presence of the warm-hot, virial-temperature gas in the Galactic halo has been known for years [4, 5, 6, 7, 8], however the super-virial temperature gas was recently discovered. The first robust detection was in the sightline to *1ES1553 + 113* passing close to the North Polar Spur/Loop-I region of the Galactic bubbles [9, 10]. Later, the similar temperature hot gas was detected toward three other sightlines passing close to and away from the Galactic bubbles [11]. These studies showed the presence of the hot gas in the Galactic halo, but it

¹<https://www.mpe.mpg.de/7461950/erass1-presskit>

²The CGM of the Milky Way is usually referred as the Galactic ‘halo’. CGM is a more prevalent term for external galaxies. Both the terms mean essentially the same, and we will use these terms interchangeably.

was not known how ubiquitous it is.

In this work we have detected the hot gas toward a large number of sightlines distributed all over the sky. We confirmed with high confidence that the super-virial temperature plasma is widespread in the Galaxy and it is not necessarily associated with the Galactic bubbles only (Extended Data Fig. 2). This has significant implications for our understanding of the bubbles.

The Galactic bubbles are believed to have formed by the GC feedback (e.g., [12, 13, 14]), that has generated shocks in the northern and the southern hemispheres, and these shocks have been expanding into the Galactic halo. The shape and speed of shocks travelling through the MW CGM depend on the CGM density, pressure and temperature. Thus to characterize the properties of the shocks, we examined the variation in thermal parameters of the warm-hot and the hot phases of the shocked (bubble shells) and unshocked (outer halo) plasma of the Galactic halo.

Fig. 2 shows the distribution of emission measures (EMs) and temperatures of both the thermal components as a function of Galactic longitude. We see that the EMs are significantly higher for sightlines piercing the bubbles compared to the outer halo sightlines. However, the temperatures of the warm-hot and hot components are similar in/outside the shells. X-ray surface brightness of a gaseous medium depends on its temperature as well as the EM. Our results show that the Galactic bubble shells have higher EMs but not higher temperature in comparison to the surrounding halo, contrary to the current proposed models of the bubbles [1]. Since the EM is proportional to the density square, we argue that the higher X-ray surface brightness of the Galactic bubble shells as seen in the *eROSITA* all-sky map is a result of the compressed denser gas, but it is not hotter than the surrounding medium.

Previous studies used a single temperature model with fixed relative abundances to define the X-ray emission and inferred that the Galactic bubble shells have temperature of $kT \approx 0.3$ keV [15, 16, 17, 18, 19, 20] or $kT \approx 0.4$ keV [21]. This is higher than the temperature of the MW CGM of ~ 0.2 keV, which led them to conclude that the bubble shells represent shock heated gas. Further, using the ratio of the pre- and post-shock temperatures, these works estimated the shock speed, age and energy of the bubbles (see methods). We show that the use of a single temperature model to represent the shell emission was too simplistic, leading to incorrect physical model of the bubbles. In this work using the new and better spectral models we accurately measured the temperatures, EMs and relative metal abundances of the plasma in the bubble shells, and used these parameters to estimate the shock properties as discussed below.

We estimated that the average density of the warm-hot component of bubbles is about 4 times larger than the pre-shock halo gas (see methods). For an adiabatic (non-radiative) shock, the maximum density jump possible is equal to 4, in the limit of a very strong shock with Mach number $M \rightarrow \infty$. But such a strong shock should also cause a significant increase in temperature of the ambient medium. Given that the pre- and post-shock temperatures are similar, and the compression ratio of the shock is high, we rule out that the bubble shells trace non-radiative shocks. Instead we infer that the bubble shells trace an old, near-isothermal, radiative shock (see methods). This is a paradigm shift in understanding the shocks marked by their X-ray emission.

We estimated the age of the bubbles to be 70–130 Myr assuming they have extended

118 about 14 kpc [1] above and below the Galactic plane. Whether the Galactic bubbles are the
 119 result of the AGN activity or the star-formation driven outflows is still a topic of extensive
 120 debate. The age of the bubbles provide an important clue to differentiate the two feedback
 121 mechanisms. The AGN wind driven models require small age $\sim 3 - 12$ Myr [22, 23, 24],
 122 while the stellar feedback models based on the star formation rate at the GC estimate the
 123 age of ~ 25 Myr [25, 26, 27] to ~ 200 Myr [13, 28]. Our estimated age of 70–130 Myr
 124 support the stellar activity feedback models for the formation of the bubbles. This is further
 125 supported by the suggestive evidence of super-solar abundance ratios of Ne/O and Mg/O in
 126 the bubbles plasma, indicative of core-collapse supernova enrichment.

Methods

Data Selection and Reduction

In this work we analyzed the *Suzaku* archival observations probing the eROSITA bubbles regions towards the center of the Galaxy, as well as the surrounding fields. For the Galactic bubbles regions we selected observations with exposure time of ≥ 20 ks. As can be seen in the *eROSITA* all sky map, the surrounding fields are much fainter in X-rays; therefore we selected the observations with higher exposure time of ≥ 50 ks. Further, to avoid the contamination from the Galactic disk, we chose targets at least 15 degrees above/below the Galactic plane. This yielded multiple observations of 150 and 80 fields, probing the Galactic bubbles and the surrounding regions, respectively.

We performed *Suzaku* data reduction with HEASoft version 6.29. We only used the data from the back-illuminated (BI) XIS1 detector, as this has better sensitivity at low energies than the front-illuminated (FI) XIS0 and XIS3 detectors. We combined the data taken in the 3×3 and 5×5 observation modes. We applied extra screening to the data in addition to the standard screening described in the *Suzaku* Data Reduction Guide. To minimize the detector background, we excluded times when the cut-of-rigidity (COR) of the Earth's magnetic field was less than 8 GV (the default value is COR = 2 GV). Further, we increased the filter value of the angle between *Suzaku*'s line-of-sight and the limb of the Earth (ELV), from the default value of 5° to 10° . This minimizes the excess events in the 0.5 – 0.6 keV band due to solar X-rays scattered off the Earth's atmosphere [29].

The activity of our own Sun can affect the space weather and contaminate data taken by space observatories. The Sun was at its minimum in the 11 year solar activity cycle when *Suzaku* was launched on July 10, 2005, approaching its maximum from early 2011 to 2014. Solar X-rays interact with the neutral oxygen in the earth's atmosphere and generate a fluorescent emission line at 0.525 keV [30]. This line in the soft-X-ray band can be detected by instruments on board satellites in the low-Earth orbits, like *Suzaku*. Gupta et al. [11] reported that in four *Suzaku* spectra taken in 2014, the O I intensity was about 25% to 130% of the O VII ³ intensity. The O I contamination can be minimized by removing events taken during time intervals when the elevation angle from the bright Earth limb (the DYE_ELV parameter) is larger [30], as we did.

For observations taken in 2011-2015, we carefully quantified the O I fluorescence line contamination in our analysis (for details see [11]). We examined the O I emission with respect to different DYE_ELV values ($> 20^\circ$, $> 40^\circ$, and $> 60^\circ$) and selected the best value for the DYE_ELV parameter that provided a good balance between optimizing the effective exposure time and mitigating the O I contamination. We then model the residual O I emission with a gaussian line in the spectral analysis. For observations taken before 2011 we applied standard screening of DYE_ELV $> 20^\circ$.

The goal of this work is to analyze the diffuse emission, hence it is important to remove the point sources. We generated the 0.5 – 2.0 keV images and identified the bright point sources. We selected the point source exclusion regions of radii of $1' - 3'$ (c.f *Suzaku* XRT's half-power

³At the temperatures of a few million kelvin, the O VII and O VIII emission lines are the dominant features characterizing the MW CGM or the bubbles.

diameter of 1.8' to 2.3'). Then we extracted the diffuse emission spectrum from the entire field-of-view after excluding the point source regions. We produced the redistribution matrix files (RMFs) using the *xisrmfgen* ftool, in which the degradation of energy resolution and its position dependence are included. We also prepared ancillary response files (ARFs) using *xissimarfgen* ftool with the revised recipe⁴. For the ARF calculations we assumed a uniform source of radius 20'' and used a detector mask which removed the bad pixel regions. We estimate the total instrumental background from the database of the night Earth data with the *xisnxbgen* ftool.

Spectral Analysis

We performed all the spectral fitting with Xspec version 12.11.1⁵. We modeled all the thermal plasma components in collisional ionization equilibrium (CIE) with the APEC (version 3.0.9) model and used solar relative metal abundances [31]. For absorption by the Galactic disk, we used the *phabs* model in XSPEC.

Suzaku provides an opportunity to resolve the different components of the SDXB due to its low and stable detector background even at low energies (0.3 – 1.0 keV). The SDXB spectrum is usually described by a three-component model consisting of: 1) a foreground component of LB and SWCX, modeled as an unabsorbed thermal plasma emission in CIE, 2) a background component of CXB modeled with an absorbed power-law, and 3) the MW halo emission, modeled as an equilibrium thermal plasma absorbed by the cold gas in the Galactic disk (the halo emission toward the Galactic center is dominated by the bubbles; [1]). Recently we found that in few observations an additional absorbed thermal component and/or enhanced Ne abundance is required to explain the excess emission near 0.7 – 0.9 keV in the *Suzaku* [11] and *XMM-Newton* [10] SDXB spectra.

We started with fitting the *Suzaku* SDXB spectra with a three-component model. The temperature of the foreground component was frozen at kT = 0.1 keV (e.g., [32, 33, 34, 35]), but we allowed the normalization to vary. We modeled the Galactic bubbles (or the extended CGM) emission as single temperature collisionally ionized plasma characterized by temperature (kT) and emission measure (EM), and with fixed metallicity⁶. We fixed the total metallicity to 1 (in solar units) for both the thermal components as the total metallicity and normalizations (or EM) are degenerate in the APEC model. We allowed the power-law photon index and the normalization to vary in the spectral fits.

This three-component model provided a poor fit to most of the data sets, showing strong excess emission at low ($\sim 0.4 - 0.5$ keV) and high (0.8 – 1.0 keV) energy bands. An example of the *Suzaku* spectrum for one observation showing these excess emissions is shown in Extended Data Fig. 1 (top panel).

Since N VII and Ne IX have strong transitions at 0.5 keV and 0.9 keV, respectively, we allowed the nitrogen and neon relative abundances to vary in our above model. That provided a slightly better fit but still left significant excess emission at the higher energy side (0.8 –

⁴<https://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/xisnxbnew.html>

⁵<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

⁶The X-ray emission data does not contain any line or edge of hydrogen. Thus we cannot obtain absolute metal abundances from X-ray emission data alone. Instead, the X-ray observations provide constraints on relative metal abundances, for example N/O, C/O, Ne/O.

1.0 keV). To fit the higher energy excess emission we added an additional thermal component to our model. This significantly improved the fit for most of our data sets. An example of best fit two-temperature model is shown in Extended Data Fig. 1 (bottom panel). The temperature of the second thermal component is much higher ($kT = 0.4 - 1.1$ keV) than the first ($kT \sim 0.2$ keV known as the warm-hot component); we call this the hot component.

Of our 150 sightlines that probe the Galactic bubbles region, the hot thermal component is required at the confidence (F-test probability) of $> 99.99\%$ in 55 sightlines and at $> 90.0\%$ in 80 sightlines. Only in 12 sightlines, adding another thermal component did not improve the fit. For the regions outside the bubbles, the hot component is required at the confidence of $> 99.0\%$ in 26 sightlines and $> 90.0\%$ in 51 sightlines, out of our 80 sightlines. Extended Data Fig. 2 shows the hot-component F-test probability map for all the sightlines investigated in this work.

Distribution of Thermal Parameters

Galactic Bubbles Region: The temperature of the warm-hot component from the bubble shells is consistent within errors with an average value of $kT = 0.205 \pm 0.003 \pm 0.002$ keV (statistical and systematic errors). The EMs of the warm-hot component of the bubbles regions varies greatly in the range $2.2 - 46.9 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ with a mean of $13.9 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ (and median of $12.7 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$). Overabundance of nitrogen by $1.3 - 10.3$ solar in the warm-hot phase is required for most of the observations that are not contaminated by the local O I emission. In observations contaminated by O I we were not able to constrain the nitrogen abundance, therefore we fixed that to solar. A few sightlines also require super-solar abundances of neon and magnesium compared to oxygen.

The measured temperatures and EMs of the hot gas in the bubble regions are in the range of $0.4 - 1.1$ keV and $0.4 - 13.9 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$, respectively, with mean values of 0.741 keV and $2.3 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$. The emission from the hot component is significantly fainter than that from the warm-hot component.

Extended Halo Region: The warm-hot component has a uniform temperature of $kT = 0.201 \pm 0.004 \pm 0.003$ keV and the hot component has a temperatures in the range of $kT = 0.4 - 1.2$ keV, similar to those in the bubbles regions. However, for both components, the EMs are much lower in comparison to the X-ray emission from the bubbles regions. The EMs of the warm-hot phase are in the range of $0.8 - 14.2 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ with a mean of $4.4 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$. The hot phase EMs are much lower, with the range of $0.2 - 1.5 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ with a mean of $6.1 \times 10^{-4} \text{ cm}^{-6} \text{ pc}$. We also found that nitrogen is overabundant by $1.0 - 11.4$ solar in the warm-hot phase. However, super-solar abundances of neon and magnesium compared to oxygen are not required toward any of the sightlines.

Northern vs Southern Bubbles: We compared the thermal properties of the northern ($b > 0^\circ$) and the southern ($b < 0^\circ$) bubbles. We have plotted the temperatures and EMs of the Galactic bubbles sightlines vs the Galactic latitude in Extended Data Fig. 3. The sightlines probing the northern bubble have comparatively higher EMs than the southern bubble, but their temperatures are similar. For the northern bubble, the warm-hot and the hot components have the average temperatures of $0.203 \pm 0.003 \pm 0.002$ keV and $0.734 \pm 0.018 \pm 0.010$ keV and the average EMs of $14.8 \pm 0.9 \pm 0.2 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ and $2.5 \pm 0.2 \pm 0.1 \times$

$10^{-3} \text{ cm}^{-6} \text{ pc}$, respectively. The southern bubble have similar temperatures of $0.210 \pm 0.005 \pm 0.003 \text{ keV}$ and $0.759 \pm 0.024 \pm 0.020 \text{ keV}$, but have lower EMs of $9.4 \pm 1.1 \pm 0.3 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$ and $1.6 \pm 0.4 \pm 0.1 \times 10^{-3} \text{ cm}^{-6} \text{ pc}$, for the warm-hot and hot phases, respectively.

The EM of the warm-hot component decreases with Galactic latitude out to about $b \pm 45^\circ$, then becomes comparatively uniform. The hot component EM variation shows the similar trend but is less prominent. The decrease in the EM with Galactic latitude is in agreement with the *eROSITA* X-ray emission all-sky map, which shows very bright emission at the base of the bubbles, with the surface-brightness falling monotonically away from the base. We do not find any such relation in the distribution of temperatures with the Galactic latitude. This further confirms that regions with brighter emission in the *eROSITA* all-sky map have higher EMs but are not hotter than the surrounding medium.

For the northern and the southern bubbles the total X-ray surface brightness ($0.5 - 2.0 \text{ keV}$) of the warm-hot component is $\sim 4.7 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$. Assuming the projected area of the *eROSITA* bubbles of $35^\circ \times 35^\circ \times \pi$ for each bubble (from [1]), we calculated the total flux of $\sim 6.5 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and $\sim 4.1 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for the northern and southern bubbles, respectively. Further assuming a distance of 10.6 kpc (from [1]), we estimated their luminosities to be $\sim 8.7 \times 10^{38} \text{ ergs s}^{-1}$ and $\sim 5.6 \times 10^{38} \text{ ergs s}^{-1}$.

The shock properties

The *eROSITA* all-sky soft X-ray map shows giant, bi-polar, X-ray emitting shell-like structures, called the *eROSITA* bubbles, likely produced by shocks that have been driven into the northern and the southern Galactic halo. The speed and shape of shocks depend on the total energy input and the thermal parameters of the ambient plasma. We compared the thermal parameters of the bubble shells and the pre-shock halo gas to infer the shock properties (following [36]).

Since the temperatures of both warm-hot and hot components are the same in and outside the bubbles, the bubbles trace either a weak non-radiative (i.e. adiabatic) shock or they have reached close to the equilibrium state of an isothermal radiative shock. For a weak adiabatic shock, the post-shock density can only marginally increase according to the Rankine–Hugoniot (R-H) condition for density. However, for a radiative shock, the density can increase by a large factor.

The X-ray flux of the warm-hot component is about six times larger than the hot component; thus for the shock calculations we focus on the warm-hot phase only. The gas density of the *eROSITA* bubbles shells are estimated from the measured values of the EMs. The EM is given by $n^2 L$, where n is the density (assuming a uniform medium) and L is the line of sight pathlength. The average line of sight path-length is about $L \sim 5 \text{ kpc}$, for a shell of outer radius of $\sim 7 \text{ kpc}$ and thickness of $\sim 4 \text{ kpc}$ (from [1]). This results in an average density of $n_{\text{shell}} \sim 1.6 \times 10^{-3} \text{ cm}^{-3}$ within the shells. The Galactic halo studies (both observational and theoretical) have estimated the halo density of about $2 - 5 \times 10^{-4} \text{ cm}^{-3}$ at a distance of 10 kpc (approximate location of the shells) from the GC [8, 37, 38, 39]. Adopting the unperturbed halo density of $n_0 = 4 \times 10^{-4} \text{ cm}^{-3}$ (the same as used by [1]), we calculated the compression ratio of shock of ~ 4.0 . Such a compression ratio rules out the scenario of a weak shock, and suggests that the boundaries of the *eROSITA* bubbles are tracing a

radiative shock.

Post-shock conditions of compression and heating send the shocked gas out of thermal equilibrium and consequently it radiates profusely. Eventually, the radiative cooling lowers the temperature until the gas attains a radiative balance, and very often the final equilibrium temperature is the same as the initial pre-shock temperature of the medium. A shock where the post-shock gas cools to the initial temperature is commonly referred to as an isothermal shock (see [36] for the detailed theory of shocks). As we noted above, the temperatures of the shells and of the ambient regions are similar within errors, as expected for an isothermal radiative shock.

Using the radiative shock jump condition for density, $\frac{n_{\text{shell}}}{n_o} = M^2$, we estimated the isothermal Mach number of $M \approx 2$. Then from the R-H conditions, we obtain the immediate post-shock conditions for $M = 2$, and assuming the adiabatic index $\gamma = 5/3$. For gas of temperature 0.2 keV, the sound speed is $v_s = 200 \text{ km s}^{-1}$. The pre-shock bulk velocity $u_1 (= M \times v_s) = 400 \text{ km s}^{-1}$. The immediate post-shock temperature $T_2 = 0.4 \text{ keV}$, and the pressure is about 4.7 times the unperturbed halo pressure.

Thus the shock instantaneously increases the temperature, pressure and density of the ambient medium, but then cools with radiative energy losses. Eventually the gas cools at approximately constant pressure, gets denser ($\rho \propto T^{-1}$), and the mass conservation implies it must move slowly, finally reaching asymptotic limit of $u_3 = \frac{u_1}{M^2} = 100 \text{ km s}^{-1}$.

Assuming the current location of the shock front at $\sim 14 \text{ kpc}$ [1], and bulk speed of $u_3 = 100 \text{ km s}^{-1}$ we calculated the age of the bubbles of $\sim 130 \text{ Myr}$; this is an upper limit on the age of the bubbles. We calculate the post-shock velocity $u_2 = u_1 \times \frac{(\gamma-1)M^2+2}{(\gamma+1)M^2} = 175 \text{ km s}^{-1}$. This velocity implies the age to be 78 Myr. Given that most of the expansion likely takes place with velocities u_2 and u_3 , the age of the bubbles is constrained to 70–130 Myr (though the exact lower limit would be somewhat smaller because some expansion would take place at u_1).

AGN or Stellar feedback?

The physical origin of the Galactic bubbles is still under debate. Since the discovery of the *Fermi bubbles*, there have been a lot of efforts to understand the formation mechanism of the bubbles, with several theoretical models proposed in literature. On the basis of their feedback mechanisms, these models can be broadly divided into two categories; one is the nuclear star-forming activity similar to starburst galaxies and the other is the past AGN activity of the GC supermassive black hole.

The estimated age of the bubbles may provide an important clue to differentiate between the two feedback models. The models requiring the explosive eruptions from the central AGN favor the age of the bubbles of the order of 3 – 12 Myr [22, 23, 24]. On the other hand, the star-formation driven outflow models estimate the age of the bubbles ranging from $\sim 25 \text{ Myr}$ [25, 26, 27] in case of a bursty nuclear star-formation, to $\sim 200 \text{ Myr}$ [28, 13] for quasi steady-state star-formation. Our estimated timescale of $\approx 70\text{--}130 \text{ Myr}$ for the expansion of the *eROSITA bubbles* out to their current extent, supports the models invoking star-formation driven feedback.

Metal abundance measurements provide another useful insight on the origin of the bub-

bles. In the star-formation activity scenarios, the bubbles are enriched by metals produced by SNe and stellar winds, whose abundances are different from that in the interstellar medium (ISM). On the other hand, in the AGN wind scenario, the abundance of the wind would be the same as the ambient ISM which accretes onto the GC supermassive black hole. In this work, we have measured super-solar abundances of neon and magnesium compared to oxygen toward a few sightlines passing through the bubbles, further supporting the stellar wind feedback scenario for the formation of the Galactic bubbles.

Comparison with Previous Studies

Multiple studies have attempted to characterize the X-ray emission from the Galactic bubbles [1, 15, 16, 17, 18, 19, 20]. These authors assumed a single temperature for the X-ray emitting shells, and measured it to be ~ 0.3 keV. They interpreted that this emission arises in the weakly shock-heated Galactic halo gas at ~ 0.2 keV, and they estimated a Mach number of the shock of $M \approx 1.5$ using the R-H conditions for the temperature [1, 15, 18].

We argue that the X-ray spectral model is more complex. First, we did not assume a single-temperature model to describe the X-ray emitting shell gas. We found that a two temperature model provides a better fit to both the shell gas, and the ambient halo gas. This enabled us to determine that the shock is radiative, instead of adiabatic. Secondly, previous studies used the fixed abundances ratio (0.2-0.3 solar) for the thermal model of the bubbles, which fails to detect any non-solar relative abundances (due to metal enrichment or metallicity inhomogeneity), as is commonly seen in the star-formation related feedback.

Additionally, we find that the previous claims of an adiabatic shock are inconsistent with the data. For a shock of $M = 1.5$, [1] estimated the shock speed of ~ 300 km s $^{-1}$, and consequently, the bubbles age of 15 – 25 Myr. Since their estimated age is much shorter than the cooling time of the ~ 0.3 keV gas of the order of 50 – 200 Myr, they reached the conclusion that the bubbles trace non-radiative shocks. However, their measured density of the shell plasma is in conflict with the assumption of the non-radiative shock. Their estimated 0.3 keV plasma density of 0.002 cm $^{-3}$ is a factor of about 5 times larger than their adopted value of the pre-shocked halo density of 4×10^{-4} cm $^{-3}$. However, according to the R-H condition for density for a non-radiative shock of $M = 1.5$, the density ratio should be ~ 1.7 instead. Even in the limit of a very strong shock $M \rightarrow \infty$, the density jump for a non-radiative shock is bounded by a value of $(\gamma + 1)/(\gamma - 1)$ which equals 4 for $\gamma = 5/3$. Thus we see that the shocks are not adiabatic, but instead are radiative, as we argue here.

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Fig. 1 : X-ray emission maps from our *Suzaku* survey of the Galactic bubbles and the surrounding halo regions. Figures on *top* and *bottom* show the distribution of the warm-hot and the hot phases, respectively. The color of each circle indicates temperature while the radius is proportional to the emission measure. The solid red line marks X-ray eROSITA bubbles and the red dashed lines represents the edge of the γ -ray Fermi bubbles.

Fig. 2 : Distribution of the emission measures and the temperatures of the warm-hot (top panels) and the hot (bottom panels) components of the X-ray emission. The Galactic bubbles region is shown by the grey shaded band. The red bars show the average over 10° bins.

Extended Data Fig. 1 : *Top*: Suzaku XIS1 spectrum for one observation investigated in this work with the standard SDXB three component best fit model. Excess emissions near low (0.4-0.5 keV) and high (0.8-1.0 keV) energy bands can be clearly seen in the residual plot. *Bottom*: The best-fit two temperature model with overabundance of nitrogen in the warm-hot phase. The dotted, dashed and dash-dotted lines indicate the foreground (LHB+SWCX), warm-hot and hot components, respectively. The power-law model of the CXB is not shown in the figures.

Extended Data Fig. 2 : F-test probability map for the hot-component significance required over the standard three-component SDXB model for the Suzaku observations investigated in this work. Empty circles with red crosses mark the sightlines where adding a hot thermal component did not improve the fit.

Extended Data Fig. 3 : Distributions of the EMs and temperatures in the northern ($b > 0^\circ$; $300^\circ < l < 60^\circ$) and southern bubbles ($b < 0^\circ$; $300^\circ < l < 60^\circ$). The red bars show the average over 10° bins.