Asymmetric eROSITA Bubbles as the Evidence of a CGM Wind

Guobin Mou\textsuperscript{1,2*}, Dongze Sun\textsuperscript{3}, Taotao Fang\textsuperscript{4*}, Wei Wang\textsuperscript{1,2*}, Ruiyu Zhang\textsuperscript{5}, Feng Yuan\textsuperscript{6}, Yoshiaki Sofue\textsuperscript{7}, Tinggui Wang\textsuperscript{8}, and Zhicheng He\textsuperscript{8}

\textsuperscript{1}School of Physics and Technology, Wuhan University, Wuhan 430072, China
\textsuperscript{2}WHU-NAOC Joint Center for Astronomy, Wuhan University, Wuhan 430072, China
\textsuperscript{3}California Institute of Technology, Pasadena, CA 91125, USA
\textsuperscript{4}Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, China
\textsuperscript{5}School of Physics, Henan Normal University, Xinxiang 453007, China
\textsuperscript{6}Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
\textsuperscript{7}Institute of Astronomy, The University of Tokyo, Mitaka, Tokyo 181-0015, Japan
\textsuperscript{8}School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China

*Corresponding authors: gbmou@whu.edu.cn; fangt@xmu.edu.cn; wangwei2017@whu.edu.cn

ABSTRACT

The recently revealed eROSITA bubbles (eRBs) suggest past activities in the Galactic center. The northern eRB shows noticeable asymmetric features, including distortion to the west/right and enhancement in the eastern edge, while the southern counterpart is significantly dimmer. We performed hydrodynamic simulations on the formation of eRBs, paying particular attention to the asymmetry that is also present in radio band. Our results suggest that, asymmetric eRBs favor a dynamic, circumgalactic medium (CGM) wind model, but disfavor other mechanisms such as a non-axisymmetric halo gas or a tilted nuclear outflow. The CGM wind from the east/left by north direction in Galactic coordinates blows across the northern halo with a velocity of $\sim 200$ km s$^{-1}$, and part of the wind enters the southern halo. This interaction strongly disturbs the halo, creating a dynamic halo medium and redistributing both density and metallicity within. This naturally explains the asymmetric bubbles seen in both the morphology and surface brightness. Our results suggest that our Galaxy is accreting low-abundance CGM from one side while providing outflow feedback.

Introduction

The circumgalactic medium (CGM) is the medium surrounding galaxies outside the interstellar medium (ISM) but within the virial radii. The CGM may originate from accreting the intergalactic medium, or outflowing gas supplied by supernovae or active galactic nucleus (AGNs)\textsuperscript{1,2}. The physical processes in the CGM are crucial for understanding the connection between galaxies and their large scale environment\textsuperscript{2–5}, and the missing galactic baryons\textsuperscript{5}. For the hot component of Milky Way’s CGM with temperature of $\sim 10^6$ K\textsuperscript{7}, it is typical to assume that the CGM is spherically symmetric\textsuperscript{8,9}. However, studies of the O VII absorption line centroids with improved wavelength accuracy suggests a rotation signature\textsuperscript{10}. Numerical simulations on galaxy evolution also favor a dynamic CGM in the inner tens of kiloparsecs, and the velocity of the bulk motions (including turbulence, inflow/outflow, etc.) is typically on the order of $\sim 100$ km s$^{-1}$\textsuperscript{11–13}.

The physics of CGM close to the Galactic disk is the basis for understanding the current interaction between the CGM and the Milky Way (MW). Particularly, the radial kinematics of CGM may be the most critical, and should be inevitably engraved on the gaseous halo structures such as the relic shells produced by the past activities of the Galactic center (GC). Major discoveries on the halo relics in the past
Decade include the Fermi bubbles (FBs)\textsuperscript{14}, the polarized radio lobes (PRLs)\textsuperscript{15}, and a pair of X-ray bubbles (eRBs)\textsuperscript{16}. Especially, the discovery the southern bubble by eROSITA suggests that the well known North Polar Spur (NPS) and Loop I are large scale halo structures\textsuperscript{17}, instead of a local bubble close to the solar system\textsuperscript{18} (but see\textsuperscript{19, 20} for recent study). These north-south pairs of bubbles strongly suggest that they are aftermaths of the past GC activity\textsuperscript{21, 22}, although the physical origins are still under debate\textsuperscript{23}. X-ray observations suggest that the nuclear activity should have started tens of millions of years ago, and the total energy input is $10^{55} - 10^{56}$ erg\textsuperscript{16, 17, 24}. One spectacular and important feature is that those bubbles are significantly asymmetric:

1) These northern bubbles are all tilted to the west/right side in Galactic coordinates. The western edge of the Northern eRB (NeRB) extends to $l \sim 285^\circ$ to $300^\circ$, while the eastern edge is confined within $l \lesssim 40^\circ$.

2) The NeRB shows an impressive enhancement on the east/left side, which also appears in the 408 MHz all-sky map\textsuperscript{25}, and the polarization sky map\textsuperscript{26}.

3) The Southern eRB (SeRB) is significantly dimmer (north-south asymmetry), but appears to be symmetric in east-west direction. Yet, the south PRL and south FB bend towards the west/right side significantly.

The noticeable east-west asymmetry can be conceived as aftermaths of some form of either halo medium, or nuclear outflow, which further leads to three plausible scenarios: an undetected cross wind traveling from east to west (dynamic halo medium)\textsuperscript{27–29}; a non-axisymmetric halo medium (static halo medium); or a tilted nuclear outflow\textsuperscript{30}. In this work, we test these three models with hydrodynamic simulations. Our results suggest that it is the CGM wind, rather than the other two mechanisms that leads to the observed asymmetry in the NeRB, and between the NeRB and SeRB.

**Results**

We adopt 3D Cartesian coordinates ($\hat{Z} = \hat{X} \times \hat{Y}$): the GC is placed at the origin, $Z$–axis is the Galactic polar axis, and the solar system is placed at $(X, Y, Z) = (0, -8.2 \text{ kpc}, 0)$\textsuperscript{31}. Simulation details are presented in Method.

We first introduce the CGM wind model (Figure 1b). The source of the CGM wind is unclear. It could be triggered by the relative motion of the MW in the Local Group toward the direction of M31 with a velocity of around 100 km s$^{-1}$\textsuperscript{132, 33}. Cosmological simulations on the Local Group show that the hydrostatic equilibrium (HSE) of the CGM is severely disrupted and the gas motion with a velocity exceeding 100 km s$^{-1}$ appears at tens of kilo-parsecs near the MW\textsuperscript{12}. Such a flow could be the origin of the CGM wind traveling in the halo above the Galactic disk. In our simulations, the nuclear outflow is turned on after 360 million years of the CGM wind – halo medium interaction, in which the CGM wind is injected from east by north towards the GC. Snapshots of the fiducial run are plotted in Figure S1. The morphology and surface brightness of the simulated eRBs in 0.6–1 keV band in the fiducial model are consistent with those of the observations\textsuperscript{16} (Figure 1). The stronger shock on the windward side leads to stronger density compression and higher temperature (Figure 2d, 2e), resulting in a brighter bubble edge on the left side. For the shocked CGM, the density is $\sim 3 \times 10^{-3}$ $m_H$ cm$^{-3}$ ($m_H$ is hydrogen atomic mass) and the temperature is $\sim 3 \times 10^6$ K (Figure 2d, 2e), which are consistent with observations\textsuperscript{24, 34}. Affected by the CGM wind, the northern halo gas is compressed and becomes denser, while the southern halo gas is partially stripped by the CGM wind entering the southern halo by the side of the Galactic disk. Overall, the gas density in the southern halo becomes significantly lower than that of the northern halo (Figure 2b), leading to a dimmer SeRB compared with the NeRB (north-south asymmetry). Shielded by the Galactic disk, the southern halo gas with low height does not suffer much from the CGM wind. The SeRB is
dominated by the shocked gas with lower height of $|z| \lesssim 7$ kpc (Figure 3a, 3b), which appears symmetric. The southern cavity in higher latitude is bent by the CGM wind, leading to the prominent deflection of the projected cavity (Figure 3a, 3b). The nuclear outflow probably carries cosmic ray electrons (CREs), which are bounded within the contact discontinuity (the boundary of the cavities) and produce polarized synchrotron emission in magnetic field. Thus, the bending cavities may correspond to the bending PRLs that are roughly filling eRBs. Such contradiction in the east-west symmetry/asymmetry of the SeRB/south PRL is difficult to explain in the other two scenarios.

The emission measure (EM, defined as $EM = \int n_e^2 dl$) distribution map of the 0.3 keV plasma (0.2–0.4 keV) is shown in Figure 3c with $|Z| < 2$ kpc masked out. For the NPS, our simulated EM value declines from a maximal value of $\sim 0.14$ cm$^{-6}$ pc at $b \sim +30^\circ$ to $\sim 0.06$ cm$^{-6}$ pc at $b \sim +60^\circ$. The EM in the southern halo is significantly lower, and it is $0.01$ cm$^{-6}$ pc at the cap of the South FB ($b \sim -50^\circ$). According to X-ray observations along the NPS near $b \sim +30^\circ$ and $+60^\circ$, and the cap of the South FB, the inferred EM of the 0.3 keV plasma is $\sim 0.1^{36}, 0.021 - 0.063^{37}$ and $\sim 0.01$ cm$^{-6}$ pc$^{36}$, respectively, consistent with our simulations. We define the fraction of emission measure of initial halo component as $\chi_{init} \equiv EM_{init}/(EM_{init} + EM_{wind})$, and plot the distribution map of $\chi_{init}$ in Figure 3d. For the high-latitude parts ($b \gtrsim 30^\circ$) of the NeRB, the CGM wind makes the main contribution. Moreover, for the south halo, the high-metallicity medium is pushed to the right side by the CGM wind, resulting in a brighter edge of SeRB on the right side relative to the left. This is also in agreement with observations.

The main parameters of the fiducial model are: the kinetic luminosity or power $L_k = 4 \times 10^{41}$ erg s$^{-1}$ in the form of AGN outflow, and $v_{CGM} = 160$ km s$^{-1}$ ($\rho_{CGM} = 7.5 \times 10^{-4} m_H$ cm$^{-3}$). Correspondingly, the age of the eRBs is 19 million years, and the total input energy of nuclear outflow is $2.4 \times 10^{56}$ erg. The implied mass inflow rate of the CGM wind towards the MW is 3.0 solar mass per year. Results for different $L_k$ are listed in Supplementary (Figure S3). Although we did not include the magnetic field and cosmic rays (CRs), nor did we conduct a thorough investigation of the cross-section of the CGM wind, we can still understand the approximate amount of energy required to form the eRBs, and the rough strength of a cross wind required for the asymmetric feature from these preliminary studies.

We also explored the effect of velocity of the CGM wind, by simulating the cases of a weak CGM wind with $v_{CGM} = 100$ km s$^{-1}$, and a strong CGM wind with $v_{CGM} = 300$ km s$^{-1}$ (Figure S4). The results from these two simulations significantly deviate from observations, and we conclude that the CGM wind velocity should be around 200 km s$^{-1}$. Correspondingly, the preliminary estimated mass inflow rate of the CGM wind towards the MW is roughly between 1.9 (weak wind) and 5.6 (strong wind) solar mass per year.

For non-axisymmetric halo-medium model, a higher density on the east side is expected, which will result in a slower shock and a stronger X-ray radiation (higher density) on the this side. However, ignoring magnetic field and non-thermal gas, for an axisymmetric gravitational potential ($\partial \Phi/\partial \phi = 0$), the halo gas distribution in hydrostatic equilibrium (HSE) must also be axisymmetric, i.e., $\partial \rho/\partial \phi = 0$ and $\partial T/\partial \phi = 0$. If there is any difference in density at different azimuths $\phi_1$ and $\phi_2$, the equilibrium condition in radial direction ($\partial P/\partial r = -\rho \partial \Phi/\partial r$, $P$ is the pressure) will lead to different distribution slopes of $P$ along $r$ at $\phi_1$ and $\phi_2$, which will break the HSE condition in $\phi$-direction (i.e., $\partial P/\partial \phi = 0$). If the initial density in the half simulation box of $X < 0$ is higher than the other half, the halo medium redistributes into an axisymmetric form after the timescale of the sound speed traveling through the characteristic size of the “uneven” region. The non-axisymmetric halo medium model may still makes sense, considering that the MW hosts a barred bulge in which the half-length of the bar is 5 kpc and the angle of its major axis to the Sun-GC line of sight is $+28^\circ$.$^{38}$ The gravitational potential of “bar/bulge” leads to the non-axisymmetric distribution of the halo medium, which is more concentrated along the major axis of the bar. In this model, the barred gravitational potential is set to be the solution of the Poisson equation of a bar-like density.
distribution (see Method). However, it fails in accounting for the distortion feature of the NeRB (Figure 4). Thus, the distortion feature requires a very strong factor, which exceeds the contribution of the barred gravitational potential.

Because 100 pc-scale X-ray chimneys and radio bubbles in the GC appear to be distorted with an angle of 7° (measured clockwise from the northern axis, alternatively, position angle PA=−7°), and the expanding molecular ring surrounding the central molecular zone (CMZ) inclines from the galactic plane on the sky by 9° (PA=−9°), a titled nuclear outflow scenario seems plausible for asymmetric bubbles. A titled nuclear can be formed if it is originated in a titled accretion disk, regulated by an asymmetric circumnuclear medium, or pushed aside by a nearby supernova. We performed a series of hydrodynamic tests for this scenario. The tilted angle of the nuclear outflow with respect to the Galactic pole is set to be $\alpha_{\text{out}}$, and we tested the cases of $\alpha_{\text{out}} = 7°, 17°$ and $37°$ (PA=−$\alpha_{\text{out}}$, respectively. The kinetic luminosity of the outflow is fixed at $L_k = 4 \times 10^{41}$ erg s$^{-1}$. We show the case of $\alpha_{\text{out}} = 17°$ in Figure 4 and present other cases in Figure S6 and S7. In order to explain the distorted NeRB, the nuclear outflow must point to the right side in the northern halo, no matter where the outflow entering the southern halo points. Regardless of the specific cause for the tilted outflow and specific outflow parameters (regulated by a distorted CMZ in our tests), this always results in a stronger forward shock on the right side in the northern halo, which is most critical difference compared to the CGM wind model. However, the 408 MHz radio map and the polarized radio sky show that the left edge of the northern radio bubble associated with NeRB is noticeably brighter, suggesting the shock on the left side should be stronger. This contradicts the titled nuclear outflow model, while it is in agreement with the CGM wind model. Moreover, some northern structures tracing the GC activity on a timescale of several million years appear symmetric about the polar axis, challenging the titled nuclear outflow model. These structures includes the X-ray cone stretching up to $b = +20°$ with a base connected to the GC and the neutral hydrogen clouds extending up to $b \sim +10°$.

Discussion

The outer boundary of SeRB on the Galactic west/right side may not be well defined (see Figure 1a): roughly along the 21h–longitude ($l = 315°$) or the 18h–longitude ($l = 270°$). We speculate that the extended X-ray structure along 18h–longitude may be relics of an earlier GC activity. Even if the 18h–longitude is the “real” boundary of SeRB, such a more extended structure on the right side is still consistent with the CGM wind scenario. In this case, however, the parameters of the CGM wind require fine-tuning so that the CGM wind in the southern halo can travel faster.

The existence of a CGM wind has been discussed as a possibility for the asymmetric northern X-ray bubble without, or with quantitative calculations. However, limited by the knowledge of halo bubbles at that time, the location of the northern bubbles in X-ray and radio band (halo or near the solar system) were under debate, and none of these studies can rule out the other two scenarios. Combining the new observations in recent years including confirming the bubble’s location in halo and revealing asymmetric halo bubbles in multiband, we investigate the physics behind the asymmetry. By simulating the eRBs and taking into account the associated radio structures, we find that a putative CGM wind can naturally account for all of the asymmetric features, while neither of the other two scenarios can.

Limited by the spectral resolution of the present X-ray telescopes, Doppler motions of a hot CGM within several hundreds of km s$^{-1}$ are difficult to identify. This could be directly observed by the future high energy-resolution telescopes such as the Hot Universe Baryon Surveyor (HUBS) and Athena.

Note that these 100 pc-scale structures are not necessarily related to giant halo bubbles, but may be related to the GC supernova or AGN in recent few hundred thousand years.
Current clues may be available in metal abundance. The CGM wind model predicts that the metallicity in the NeRB ($b \geq 30^\circ$) should be low and uniform, and that in the middle part and right edge of the SeRB should be high. We note that the high latitude “north-cap” ($b = +50^\circ$ in the X-ray bubble) shows a significantly low metallicity ($Z \sim 0.075Z_\odot$), while the “south claws” in lower latitudes ($b = -16^\circ$ in the X-ray bubble) shows a much higher metallicity of $0.72Z_\odot$. Moreover, Suzaku reported that the metal abundance is $\sim 0.22Z_\odot$ at the edge region of northern FB ($b > 42^\circ$), and $Z < 0.5Z_\odot$ in the brightest 3/4 keV emission region of the NPS ($l = 26.8^\circ, b = +22.0^\circ$). These observations are generally consistent with the predictions of the CGM wind model, and observational data with higher quality is required for verification. Moreover, if low-ionization warm gas exists in the CGM wind, it may exhibit UV/optical signatures with a steepening radio spectrum above several GHz (assuming synchrotron losses dominate). A new population of hard-spectrum CRe is supplied with enhanced ionization levels in the Magellanic Stream and FBs with lower heights are from the second GC outburst happening 10$^6$ years ago as suggested by the enhanced ionization levels in the Magellanic Stream. Nowadays, due to inverse Compton scattering and synchrotron losses, the CRe spectrum from the first outburst steepens at $\sim 10$ GeV, leaving the PRLs as relics with a steepening radio spectrum above several GHz (assuming $B = 6 \mu G$). In the second outburst, the nuclear outflow quickly reaches a height of $\sim 10$ kpc without requiring a high energy budget due to the low resistance in the underdense cavities. A new population of hard-spectrum CRe is supplied with...
the outflow, and theoretical studies have proved that the same population of CRe can reproduce both the WMAP haze and FBs. Modeling multiwavelength structures involves complex processes such as the magnetic field, transportation/diffusion and cooling of cosmic rays, which can be performed in the future with emerging observations.

**Method**

Simulations are performed using ZEUSMP code. We choose the 3D Cartesian coordinates: the GC is placed at the origin, \(Z\)-axis is the Galactic polar axis, and the solar system is placed at \((X,Y,Z) = (0,-8.2 \text{kpc},0)\). The plane of \(Z = 0\) and \(\sqrt{X^2 + Y^2} \leq 20 \text{kpc}\) is set to be the Galactic disk, and \(v_z\) is forced to zero there. The computational domain extends from \(-36 \text{kpc}\) to \(+36 \text{kpc}\) in \(X\)-direction, \(-22 \text{kpc}\) to \(+22 \text{kpc}\) in \(Y\)-and \(Z\)-direction, and is divided into \(464 \times 360 \times 360\) non-uniform meshes. The common ratio of the adjacent grid-length is \(dX_{i+1}/dX_i = dY_{i+1}/dY_i = dZ_{i+1}/dZ_i = 0.99\) for negative \(X, Y, Z\), \(dX_{i+1}/dX_i = dY_{i+1}/dY_i = dZ_{i+1}/dZ_i = 1.009\) for positive \(X, Y, Z\). The boundaries are set to be outflowing.

Initially, we assume that the halo medium is in hydrostatic equilibrium (HSE) with a temperature of \(2.0 \times 10^5 \text{K}\), and is symmetric with respect to the Galactic disk. Here we do not include the cold/warm ISM component near the Galactic disk. If including the cold/warm ISM near the disk (the latter requires higher mesh resolution and more complex motion settings), the density there will be higher, and the shock driven by GC activity will become slower, forming dumbbell-shaped halo bubbles with a narrower waist close to the disk. However, this only affects the part of the simulated eRBs with \(|b| \lesssim 20 – 30^\circ\), and does not change our main conclusions.

For the CGM wind model, the wind is injected from a spherical surface with a radius of 30 kpc cut by \(Z = 0\), \(Z = 18 \text{kpc}\), \(Y = \pm 22 \text{kpc}\), with a velocity of \(\vec{v} = -v_{\text{CGM}}\vec{e}_r\) (along radial direction towards the GC), a density of \(\rho_{\text{CGM}}\), and a temperature of \(1 \times 10^6 \text{K}\). Due to the MW’s gravity and thermal pressure, the wind should move neither parallelly nor ballistically. The initially anti-radial motion for the injected CGM wind is a simplification, and the wind direction will be self-regulated under its thermal pressure when approaching the GC (Figure 2b). The setup of the CGM wind will affect the kinematics of the CGM, the projected eRBs, and the formation of cold clouds and their motions, but this is a second-order correction for the model and can be left for thorough investigations in the future. The metal abundance is set to be \(0.2Z_\odot\) for the CGM wind, and \(0.5Z_\odot\) for the initial halo medium which may be enriched by stellar feedbacks. After the CGM wind has swept across the simulation box \((\sim 360 \text{Myr})\), the material’s distribution settles into a slowly-evolving state, forming a dynamic halo atmosphere (Figure 2b), and we start to inject nuclear outflow. The two main free parameters here are the kinetic luminosity of the nuclear outflow \(L_k\) and CGM wind injecting velocity \(v_{\text{CGM}}\). We note that at \(X = -10 \sim -20 \text{kpc}\), the pressure difference at above and below the Galactic disk induced by the CGM wind is \((2 - 4) \times 10^{-13} \text{dyn cm}^{-2}\). The pressure in the midplane there is unclear: if it is similar to that in the vicinity of the Sun which is several times \(10^{-12} \text{dyn cm}^{-2}\) (including both thermal and non-thermal pressure), the CGM wind will not deform the Galactic disk. If it does exceed the midplane pressure at some distance, however, the CGM wind will travel across the disk and penetrate into the southern halo, and simulation setup in this case requires fine-tuning (e.g., reducing the disk radius).

The nuclear outflow is set to be in the form of an AGN outflow. Although Sgr A* is quiescent currently, observations suggest that it probably has been active during the past several million years. It is known that star-formation in the central molecular zone (CMZ) can also drive nuclear outflow, and may account for the 100 pc–scale GC bubbles or 1 kpc–sized outflowing clouds. Over the past 30 Myr, an estimated \(3 \times 10^4\) supernovae have exploded in the GC, indicating that the averaged power of
supernovae is \(10^{40} \text{ erg s}^{-1}\). With this power \((4.5 \times 10^{40} \text{ erg s}^{-1})\) and a higher halo metallicity, however, the simulated surface brightness of the NeRB in star-formation wind model is only half of the observed\(^{61}\). Furthermore, if considering supernovae randomly exploded in the CMZ, the high density environment with a column density of \(> 10^{22} \text{ cm}^{-2}\)\(^{62}\) is a challenge for transporting the energy into Galactic halo. Due to the radiative cooling, the supernova energy rapidly reduces after leaving the Sedov-Taylor phase\(^{63}\), and the radius of a supernova remnant at this moment is \(< 10 \text{ pc}\), considering that the averaged gas density of the CMZ is \(\gg 1 m_H \text{ cm}^{-3}\) \((\text{see}^{64}\) for example). Even if considering the lower filling factor of high density neutral gas in the CMZ, numerical simulations suggest that averaging over time, only 10–20 per cent of the supernova energy budget can be injected into the halo\(^{65}\). Thus, before breaking out of the CMZ, the supernova energy should have undergone significant radiative loss, and the power injected into the halo should be lower than the ideal case of \(10^{40} \text{ erg s}^{-1}\). This physical process was not included in previous star-formation model\(^{30,61}\). In contrast, however, the AGN outflow soon opens a low-density channel and the following outflow runs freely into the low-density halo without losing much energy. Taking these factors into account, we think that AGN is more likely to be the energy source for the eRBs, unless there is evidence that the power delivered by the GC supernovae to the halo is much higher than the current estimation.

We simplify the AGN outflow to be intrinsically isotropic for the following reasons. First, the anisotropy will be smoothed out by the surrounding CMZ. Second, AGN activities may have repeated for several times during a timescale of 20 million years (e.g.,\(^{66}\), rather than in the form of a continuous activity as simplified in our simulations. Averaged over multiple activities, the anisotropy will be further smoothed out. Due to the CMZ stretching along the Galactic disk\(^{67}\), the outflow is regulated to be beamed at the polar direction\(^{68,69}\). As a consequence, the nuclear outflow enters the halo in the form of conical outflow roughly perpendicular to the Galactic disk, which is consistent with the conical outflowing clouds extending up to \(|b| \lesssim 10^{-44}\), and the X-ray cone stretching up to \(b = +20^\circ\). In order to capture the process of CMZ regulating outflow, we performed small-scale simulations separately within a much smaller 3D box (±0.4 kpc in each direction) and higher resolutions (grid size 3 pc). In these small-scale simulations, the outflow is injected isotropically within \(r \leq 10 \text{ pc}\) (\(r\) is galactocentric distance), and its velocity is fixed at \(1 \times 10^4 \text{ km s}^{-1}\) which corresponds to typical values in the AGN outflow scenario\(^{68,69}\). The CMZ initially is set as a disc-like structure with aspect ratio \(H/R\) of 0.2, and outer radius of 200 pc. Its density is \(100 H cm^{-3}\) (a total mass of \(1.7 \times 10^7 M_\odot\)), and its motion is Keplerian rotation in the gravitational field (see below). We relax the CMZ for 20 million years before launching outflow. Due to the high ram pressure, the AGN outflow cleans up the CMZ materials in the inner tens of parsecs, and naturally results in the observed ring-like CMZ, as noted by\(^{68}\). After breaking out of the CMZ in the thinnest direction soon (perpendicular to the CMZ), a quasi-steady and continuous supersonic biconical outflow forms (see Figure S2), and its physical parameters are imported in the large-scale simulations (Galactic scale) as the injection form of the nuclear outflow.

The hydrodynamic equations are:

\[
\frac{d\rho}{dr} + \rho \nabla \cdot \vec{v} = 0, \tag{1}
\]

\[
\frac{d\vec{v}}{dr} = -\frac{1}{\rho} \nabla p - \nabla \Phi, \tag{2}
\]

\[
\rho \frac{d}{dr} \left( \frac{e}{\rho} \right) = -p \nabla \cdot \vec{v} - C. \tag{3}
\]
The gravitational potential $\Phi$ is consisting of three components, namely\textsuperscript{70}:

$$\Phi(\vec{r}) = \Phi_{\text{halo}} + \Phi_{\text{disc}} + \Phi_{\text{bulge}} = \nu_{\text{halo}} \ln(r^2 + d_h^2) - \frac{GM_{\text{disc}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}} - \frac{GM_{\text{bulge}}}{r + d_b} \quad (4)$$

where $r = \sqrt{R^2 + z^2}$ is the distance to the GC, $z$ is the height to Galactic plane, $\nu_{\text{halo}} = 131.5$ km s$^{-1}$, and $d_h = 12$ kpc; $M_{\text{disc}} = 10^{11}$ M$_\odot$, $a = 6.5$ kpc, and $b = 0.26$ kpc; $M_{\text{bulge}} = 3.4 \times 10^{10}$ M$_\odot$ and $d_b = 0.7$ kpc. For the non-axisymmetric halo medium model, to mimic the bar's effect, we add an asymmetric quadrupole gravitational potential by solving the Poisson equation of a bar-like density distribution\textsuperscript{39}:

$$\Phi_{\text{bar}} = \Phi_2(r) \cdot \sin^2 \theta \cdot \cos(2\phi),$$

where $r = (X^2 + Y^2 + Z^2)^{1/2}$, $\theta$ is the polar angle ($\theta = 0$ is the Galactic pole), $\phi$ is the azimuthal angle measured from bar ($\phi = 0$ is the direction of the bar). Radiative cooling term $C$ is calculated according to the metallicity\textsuperscript{71}. However, we force the temperature of the CMZ to be $10^4$ K, otherwise it will collapse into a very thin layer. The density distribution is initialized as $\rho(\vec{r}) = \rho_0 \exp\left[-\frac{\mu m_{\text{H}}}{k_B T}(\Phi(\vec{r}) - \Phi(0))\right]$, where $\rho_0$ is the density at $\vec{r} = 0$ and normalized as $8.5 \, m_{\text{H}}$ cm$^{-3}$ (or $10 \, m_{\text{H}}$ cm$^{-3}$ for tilted nuclear outflow model) following observational suggestions\textsuperscript{72} (see Figure 2a for the initial density distribution). Moreover, the effect of the rotation of CGM is also investigated. We simply assume that the rotation of the isothermal CGM is along the azimuth direction and satisfies $\nu_{\text{rot}}(R, z) \equiv f \cdot \nu_{\text{Kepler}}(R, 0) = f \cdot (R \sqrt{\Phi(z = 0)})^{1/2}$, where $0 \leq f < 1$ ($f = 0$ means no rotation). Thus, the initial density of CGM in equilibrium is given by\textsuperscript{73}

$$\rho(\vec{r}) = \rho_0 \exp\left\{ -\frac{\mu m_{\text{H}}}{k_B T} \left[ \Phi(\vec{r}) - f^2 (\Phi(\vec{r})|_{z=0}) \right] \right\}. \quad (5)$$

We investigated three cases for the CGM rotation: $f = 0.3$, 0.5 and 0.7, and for each case we adjust the value of $\rho_0$ to match the simulated X-ray surface brightness approximately within the observational range. The results are presented in Figure S7 and S8.

The cosmic X-ray background in 0.6–1.0 keV is set to be 2 counts s$^{-1}$ deg$^{-2}$\textsuperscript{74}. The X-ray surface brightness is calculated with simulation data and the Astrophysical Plasma Emission Code\textsuperscript{75}. The brightness in 0.6–1.0 keV band $F_x$ (counts s$^{-1}$ deg$^{-2}$) is $F_x = A_{\text{eff}} \cdot (4\pi)^{-1} \int j_x(T) dl$, where $dl$ is the length element along the line of sight, $j_x(T)$ is the X-ray volume emissivity, $T$ is the gas temperature given by $kT = \mu m_{\text{H}} P/\rho$ ($\mu = 0.61$), and the field-of-view averaged effective area $A_{\text{eff}}$ is fixed at 1000 cm$^2$\textsuperscript{76}. The absorption of X-ray is dominated by the column density of foreground neutral gas\textsuperscript{77}. According to the optical depth map in 0.44–1.01 keV range\textsuperscript{22} (slightly different from the 0.6–1.0 keV range investigated here), the optical depth is below $\sim 0.3$ for the most areas of the eRBs. An exception is the Aquila Rift at $(l, b) \sim (25^\circ, 12^\circ)$, where the simulated X-ray should be strongly obscured. In general, neglecting X-ray absorption does not affect the mid- and high-latitude part significantly. As we do not include the rotation of ISM or cold/warm gas near the Galactic disk, X-ray emission below the height of $|z| = 2.0$ kpc is masked out when calculating the surface brightness.

The nature of Loop I/NPS. Whether the location of Loop I and the NPS is local or in GC–distance has been hotly debated for decades. It is suggested the radio Loop I and the X-ray NeRB should be the same physical structure as they spatially overlap with each other. The radio emission should come from the synchrotron radiation of CRe accelerated by the forward shock. Thus, the discovery of the SeRB provides a convincing evidence to support the GC–distance picture, which is also supported by the foreground X-ray absorption by the Aquila Rift clouds at a distance of 1 kpc\textsuperscript{22,78} and the high emission measure of 0.3 keV plasma accounting for the X-ray NPS\textsuperscript{37}. Yet a recent work\textsuperscript{20} investigated the optical polarization angles of nearby stars induced by the foreground dust\textsuperscript{19,79}. They find that the starlight polarization angles
Figure 1. Panel (a) shows the observed X-ray map in 0.6–1.0 keV band. The edges of the NeRB and FBs are marked with cyan diamonds (coordinate values in Supplemental note1), and blue triangles, respectively. Panel (b) sketches the associated multiwavelength structures and the CGM wind model accounting for the asymmetric eRBs. The yellow areas represent the radio Loop I in the northern halo and the eRBs, and the orange region marks the NPS as the brightest part of Loop I and the NeRB. The green areas (including the blue inside) are 2.3 GHz PRLs. The blue areas mark the WMAP haze in 23–41 GHz and FBs. Panel (c) shows the simulated eRBs for the CGM wind model in units of counts s$^{-1}$ deg$^{-2}$ at $t = 360 + 19$ Myr. We masked the region of $|Z| < 2$ kpc. Edges of the observed NeRB and FBs are plotted in white line with diamonds and yellow dashed line, respectively. The red crosses mark the bound of the observed PRLs. Panel (d)-(f) show the X-ray surface brightness profiles cut at $b = \pm 40^\circ$, $\pm 50^\circ$ and $\pm 60^\circ$, respectively, in which the observed profiles for comparison are plotted with dashed lines. Our results generally match the observational data, especially the asymmetric features.

at $b > 30^\circ$ are essentially aligned with that of the radio NPS in tens of GHz, and thereby argue that this part of NPS should be limited within $\sim 100$ pc. However, the orientation of the local dust grain could be affected by nearby Sco-Cen OB associations, independent of the background bubble. Moreover, regarding Loop I/NPS as a local structure may not be self-consistent in the presence or absence of shock. The origin of relativistic electrons accounting for Loop I, the sharp edge of the NeRB and the hot gas of 0.3 keV accounting for the NeRB indicate that shock should exist with a velocity of $\sim 300$ km s$^{-1}$. However, this conflicts with the low velocity of colocated H I of around 10 km s$^{-1}$ as observed, and is a challenge for the existence of H I and dust grains. Thus, although the nature is still controversial, we believe that radio and X-ray Loop I/NPS is a GC–distance halo structure, while it is coincidentally overlapped by the foreground local dust and H I. Both the prominent east–west asymmetry of Loop I/NPS and the faintness of its southern counterpart (north–south asymmetry) are caused by the CGM wind.

Data availability

Source data are available from the corresponding author upon reasonable request.

Code availability

The simulations were performed using the code ZEUSMP, publicly available at http://solarmuri.ssl.berkeley.edu/~ledvina/public/code/. The other codes that support the plots within this article are available from the authors upon reasonable request.
**Figure 2.** Panel (a) shows the initial density distribution of the hot halo \((Y = 0)\), and the grey line denotes the Galactic disk. Panel (b) shows the density and velocity (arrows) at \(t = 360\) Myr, with black contours representing the boundary of initial halo medium. Due to the shielding of the Galactic disk, density and metal abundance in northern and southern halos are quite different. In northern halo, the materials at \(Z \gtrsim 3\) kpc are incoming CGM wind. In southern halo, the region of \(|Z| \lesssim 4\) kpc is almost unaffected, and the initial halo medium even stretches to \(Z \sim -20\) kpc in leeward region. Panel (c) presents the metallicity and velocity distribution at \(t = 360 + 19\) Myr (the metallicities of both the nuclear outflow and the initial halo are set to be 0.5 \(Z_{\odot}\)). Distributions of density and temperature at \(t = 360 + 19\) Myr are presented in (d) and (e), respectively. Both cavities inflated by nuclear outflow appear tilt toward the CGM wind’s moving direction. Panel (f) presents a 3D view of the density distribution. Coordinate values are in units of kpc.
Figure 3. Panel (a) and (b) show segmented X-ray projections of $2 < |Z|/\text{kpc} < 7$ and $|Z|/\text{kpc} > 7$, respectively. The green lines represent the outlines of bubble cavities filled by nuclear outflow ($T > 6 \times 10^6 \text{K}$) which may account for the PRLs\textsuperscript{15} (red crosses). The morphology of PRLs definitely bend towards the right/west, exhibiting a large C–shaped structure which is frequently observed in other radio galaxies\textsuperscript{81} as aftermath of a cross wind acting upon the bubbles\textsuperscript{82}. Panel (c) exhibits the EM of 0.3 keV plasma with $|Z| > 2 \text{kpc}$. Panel (d) shows the distribution of $\chi_{\text{init}}$ with $|Z| > 2 \text{kpc}$. 
Figure 4. Density distributions and X-ray maps for the non-axisymmetric halo medium (upper, $t = 19$ Myr) and tilted nuclear outflow model (lower, $t = 18$ Myr). Colorbars of density are the same as Figure 2. The orange and red lines in left panels represent isotherms of $3 \times 10^6$ and $4 \times 10^6$ K, respectively. The green lines mark the cavities filled with the nuclear outflow. In both cases, the outlines of the eRBs appear essentially symmetric in the east–west direction. In the titled outflow model, the projected X-ray map presents a brighter substructure on the left side in the northern halo (bottom right). This is due to the high-density gas being lifted up rather than just being pushed aside by the outflow (see the yellow region at $Z \approx 8$ kpc in the bottom left panel). Apart from this substructure, the northern bubble is brighter on the right due to stronger compression. Note that for both models, the metallicity of halo medium is reset to be $0.2Z_\odot$. 

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Author contributions statement
G.M. presented the idea and wrote the manuscript. G.M. and D.S. made the simulations. T.F., W.W. and Y.S. provided valuable feedback. R.Z. helped to calculate the X-ray emission and all co-authors gave comments on the contents of the paper.

Additional information
The authors declare that they have no competing financial interests.
**Supplementary Information**

**Coordinates of the NeRB’s Edge**

Coordinates \((l, b)\) of the points marking the contours of NeRB are listed below:

\[(29.3, 8.2), (36.1, 17.2), (37.5, 34.6), (39.0, 55.8), (36.4, 66.5), (6.1, 78.3), (-56.1, 76.2), (-66.8, 69.5),
-52.0, 48.6, -53.2, 61.2, -41.5, 66.8, (0.0, 60.0), (-1.6, 48.7), (9.0, 35.2), (11.7, 25.5), (17.0, 15.2),
-45.0, 30.0, (-60.0, 30.0), (-53.0, 20.0).\]

**Snapshots of the CGM Wind Model**

Snapshots of density evolution in the fiducial run of the CGM wind model are plotted in Figure S1.

**Small-scale Simulations**

The small-scale 3D simulations are aimed at capturing the process of CMZ regulating the nuclear outflow, and generating the parameters of nuclear outflow injected into the Galactic scale simulations. The biconical outflow is supersonic with a ram pressure much higher than that of ISM/CGM, transportation of material and energy given by small-scale simulations is one-way (outward), and the large-scale environment outside does not affect the small-scale domain.

**Dependence of the Results on the Kinetic Luminosity \(L_k\)**

The results for different \(L_k\) in the CGM wind model are shown in Figure S3. The surface brightness of simulated eRBs is significantly affected by \(L_k\). Given the halo temperature of \(2 \times 10^6\) K\(^7\), the post-shock CGM (or CGM wind) density and temperature required for modeling the eRBs\(^{24,34}\), there is no much space for adjusting the kinetic luminosity. Although it can take a longer time for a lower \(L_k\) to supply enough energy to inflate bubbles, the temperature of post-shock CGM (especially the southern halo which does not suffer much from the CGM wind) will become lower, leading to dimmer eRBs and deviating from the X-ray spectral shape, and vice versa. Based on our preliminary tests, the approximate range of
the averaged kinetic luminosity should be between $2 \times 10^{41}$ and $8 \times 10^{41}$ erg s$^{-1}$. One could adopt a lower kinetic luminosity by setting a higher initial CGM temperature (e.g., $2.5 \times 10^6$ K$^7$). However, this will result in a significantly low brightness contrast of the eRBs in background compared with observations.

**Dependence of the Results on the Velocities of the CGM Wind**

We tested the results with different injection velocities of the CGM wind $v_{\text{CGM}}$, and plotted the representative cases of the weak and strong CGM wind in Figure S4.

**Effect of CGM Temperature**

For the non-axisymmetric halo medium model, the density distribution of the CGM could be affected by the initial temperature. We investigated the effect of the initial temperature by setting it to $2.5 \times 10^6$ K and $1.5 \times 10^6$ K (the fiducial value is $2 \times 10^6$ K). The results are shown in Figure S5. Both cases failed in modeling the prominently asymmetric features as observed. We did not explore wider temperature range, since when $T_{\text{CGM}} > 2.5 \times 10^6$ K, the background X-rays will become too bright, and when $T_{\text{CGM}} < 1.5 \times 10^6$ K, the X-ray bubbles will be too dim and uneven.

**Effect of the Tilted Angle of Nuclear Outflow**

In the tilted nuclear outflow model, we have tested different tilted angles $\alpha_{\text{out}}$, and presented the cases of $\alpha_{\text{out}} = 7^\circ$ and $37^\circ$ in Figure S6. The simulated northern X-ray bubble exhibits a brighter edge on the right/east side due to stronger compression. Moreover, the outline of the northern bubble does not exhibit prominent asymmetry as observed even when $\alpha_{\text{out}} = 37^\circ$, suggesting that the asymmetry of the bubble’s outline is insensitive to the nuclear outflow’s direction. This remains true even when considering rotational CGM (see below).

**Effect of the CGM Rotation**

We have tested the effect of rotating CGM on the results (Figure S7) and investigated three different rotational speed: $f = 0.3, 0.5$ and $0.7$ (see Method for the definition of $f$). Apparently, in the non-axisymmetric halo medium and tilted nuclear outflow model, the X-ray bubbles will become narrower in the east–west direction when $f$ is higher. The reason is that when rotation is faster, the density distribution in the lateral direction will be flatter (see Equation 5), resulting in a greater resistance for the bubble to expand laterally. All of these cases failed in reproducing the prominently asymmetric NeRB as observed.
**Figure S3.** Simulation tests for the different values of $L_k$. The upper panels show the projected maps of X-ray surface brightness in 0.6–1.0 keV range. The lower panels present the corresponding density profile.

**Figure S4.** Simulation tests for weak (left, $v_{\text{CGM}} = 100 \text{ km s}^{-1}$) and strong CGM wind (right, $v_{\text{CGM}} = 300 \text{ km s}^{-1}$) cases. The upper panels show the density and velocity distributions on the slice of $Y = 0$ at $t = 360$ Myr. The lower panels show the simulated X-ray maps at $t = 360 + 19$ Myr and 360+20 Myr for both cases. Colorbars are in units of counts s$^{-1}$ deg$^{-2}$ (0.6–1.0 keV). The orange and red solid lines represent contours of $\chi_{\text{init}}$ of 20% and 50%, respectively.
Figure S5. Results of different initial CGM temperatures in the non-axisymmetric halo medium model. The panels show the 0.6–1.0 keV surface brightness. Note the colorbar in right panel is different from the left one.

Figure S6. Results of different tilted angles. The left and right panels show the results of $\alpha_{\text{out}} = 7^\circ$ and $37^\circ$, respectively. The upper panels present the 0.6–1.0 keV surface brightness (orange lines – cavities). The lower panels present the density distribution on $Y = 0$ (orange lines – $3 \times 10^6$ K, red lines – $4 \times 10^6$ K).
Figure S7. Effect of rotating CGM in the non-axisymmetric halo medium and tilted nuclear outflow model. The rotation of CGM mainly affects the width of the bubbles in the lateral direction. The orange lines in the panels of $f = 0.5$ mark the bubble cavities. All these cases failed in reproducing the prominently asymmetric NeRB. Note that for the cases with $f = 0.7$, the caps of bubbles have already crossed the boundaries of simulation box (at $t = 12$ or $13$ Myr) and therefore the brightness at $|b| > 60^\circ$ is underestimated.

In addition, when rotation is incorporated, the initial CGM forms a low-density channel near the Galactic pole. Therefore, in the titled nuclear outflow model, the top of the bubble gradually moves towards to the Galactic pole due to lower resistance, forming a “)”–shaped cavity in the northern halo which is contrary to the “(”–shaped northern PRL (see the panels of $f = 0.5$ in Figure S7).

For the CGM wind model, the situation is more complicated, since the rotation of the halo medium is coupled with the parameters of the CGM wind, such as the angular momentum of the CGM wind, the CGM wind velocity $v_{\text{CGM}}$, etc. Here we only adjust one parameter of $v_{\text{CGM}}$, and pick out the results that match the observations as closely as possible (judging by the eyes on the projection 0.6–1.0 keV surface brightness) and show them in Figure S8. According to these preliminary tests, the results of modeling eRBs are not significantly improved.

High-Velocity Clouds

In our fiducial run (at $t = 360 + 19$ Myr), we find that high-velocity clouds (HVC) form from the
Figure S8. Effect of rotating CGM in the CGM wind model. The upper panels present the 0.6–1.0 keV surface brightness, and the lower panels present the density distribution on $Y = 0$. $v_{\text{CGM}}$ adopted here is 140 km s$^{-1}$ ($f = 0.3$), 120 km s$^{-1}$ ($f = 0.5$) and 120 km s$^{-1}$ ($f = 0.7$), respectively.
Figure S9. Upper panels show 3D views of gas density (only showing $\rho > 4 \times 10^{-3} \, m_H \, cm^{-3}$) at $t = 360 + 19$ Myr for the fiducial model. The minor tick marks on the axes are at interval of $5 \times 10^{21} \, cm$ (1.6 kpc). Solar system is at $(X, Y, Z) = (0, -8.2 \, kpc, 0)$. Lower panels show the projected column density and LSR velocity of clouds.

cooling of the incoming CGM wind. For the convenience of comparison with observations\textsuperscript{50}, the clouds are projected onto the sky in the Galactic Coordinate System with the anti-GC in the center (Figure S9). For the local standard of rest (LSR) velocity, we assume the standard orbital velocity of $V_{\text{sun}} = 250 \, km \, s^{-1}$\textsuperscript{183}. The clouds are concentrated in the quadrant of $180^\circ > l > 0^\circ$, $b > 0^\circ$ (infalling region of the CGM wind). The simulated cloud complex in latitude of $0^\circ - 75^\circ$ roughly resembles the observed Complex C at the similar sky area. Excepting the lower part of $b < 30^\circ$, this simulated complex exhibits a LSR velocity of $0 - 150 \, km \, s^{-1}$, and a column density of $10^{19 - 20} \, cm^{-2}$, which are also similar to those of the Complex C\textsuperscript{50}.

However, we should caution that parameters of the HVC given by our model are preliminary, since the uncertainties of current observations prevent us from further refining the simulation parameters. The injection area and the injection direction of the CGM wind are somewhat arbitrary. These will affect the final result on the formation of the clouds. The results on the HVC presented here is only to illustrate that the CGM wind scenario is not contradictory to the HVC, and furthermore, it may potentially explain the formation of HVC.

Effect of Numerical Resolution

We tested the effect of numerical resolutions by performing a lower resolution run (mesh size= $2 \times$ fiducial) and a high resolution run (mesh size= $0.6 \times$ fiducial). Comparing with the results in different resolutions (Figure S10), we find that the values of the cavity volume are 570, 480 and 460 kpc\textsuperscript{3} in the low-, fiducial- and high-resolution cases, respectively, indicating that the results rapidly converge on the resolution. The effect on the bubble morphology with different resolutions are mainly due to the opening
angles of the nuclear outflow injected into the halo, which are affected by the mesh size. When adopting smaller meshes (higher resolution), it is easier to capture the development of the Kelvin-Helmholtz (KH) instabilities. As the wavelength of the KH instability develops close to the size of the nozzle, the wobbling of the nozzle widens it and the opening angle becomes larger. In turn, when adopting larger meshes (lower resolution), the KH instabilities will be difficult to develop. The numerical resolution plays a viscous–like role (numerical viscosity), and KH instabilities are more easily suppressed in the low resolution case. It changes bubble’s morphology by affecting the opening angle of the outflow. However, the most important parameter here is the kinetic power of the outflow (almost unchanged in all the three resolutions), while the opening angle of the nuclear outflow is a secondary effect. The effect of numerical resolution does not change the main conclusions of this work.