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Simulating X-ray Observations of AGN Inflated Bubbles in High-Redshift Galaxy Clusters with AXIS

by

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Abstract

Accreting supermassive black holes emit relativistic jets along the axis of rotation. When this phenomenon occurs in a galaxy cluster, it is surrounded by the hot intracluster medium. The jets then form cavities, or bubbles, in the ICM, which can be observed in X-ray. This project assesses how AXIS, The *Advanced X-ray Imaging Satellite,* would be able to observe these cavities in the ICM. AXIS would have greater sensitivity than its predecessors, allowing it to see older cavities which have risen from their BH as well as cavities in more distant galaxy clusters. The motivation behind these observations includes determining the point at which this bubbling behavior began in the universe and determining how the bubbles may evolve over time.

We will accomplish this by simulating (using SIMX) the image that would be received by AXIS based on varying observation time, cavity size and distance from center, and brightness of the cluster.

Introduction

It is thought that there is a supermassive black hole (SMBH) at the center of every normal galaxy. These black holes can accrete gas, and become active. These active galactic nuclei (AGN) emit radiation as the accreted gas becomes heated. In the context of study on this topic, the AGN we are interested in are all in the centers of brightest galaxies in the middle of galaxy clusters. Galaxy clusters are complex structures that have formed on extremely large scales over billions of years. These clusters are composed of hot gas, up to tens of millions of degrees. The majority of their mass, however, is attributed to dark matter. The hot gas emits X-rays via bremsstrahlung radiation, which means "braking radiation". It earned this name because energetic electrons get deflected by a positively charged particle via the Coulomb force, which causes the emission of an X-ray photon; the resulting energy loss causes the electron to "brake." For reasons that are not yet entirely understood, AGN can emit relativistic jets that are observed on scales from astronomical units to megaparsecs. Theories debate the relative importance of kinetic energy and magnetic energy in these jets. The issue arises of whether these jets could be magnetically dominated, and what the physical processes behind such large scale matter flows are (Li, H. et al 2006). These jets "blow bubbles" in the intracluster medium (ICM), which can be see in figure 1.

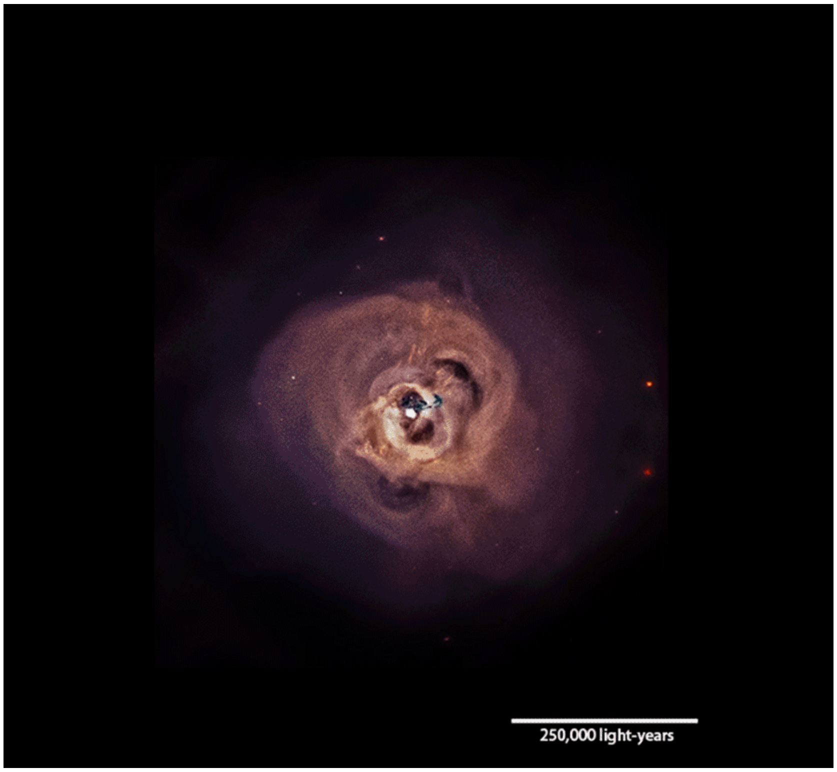

Figure 1. Chandra's best view of hot gas in the central region of the Perseus cluster, made from 16 days of observations (NASA's Goddard Space Flight Center/Stephen Walker et al.)

There are many uncertainties about the properties and evolution of these cavities. Greater study of these clusters is limited by the sensitivity of current X-ray observatories. This is why proposed future missions such as the Advanced X-ray Imaging Satellite (AXIS) may be vital in solving some of the mysteries of how these jets interact with the ICM. In particular, the higher collecting area of AXIS should allow us to see cavities in systems at higher redshifts as well as older cavities that have risen farther from the AGN. AXIS would aim to provide imaging in the 0.3-10 keV band across a 450 arcminute field of view, with an order of magnitude improvement in sensitivity compared to current capabilities. AXIS would capitalize on improvements in the construction of the mirror assembly, which would be made of about 14,000 single-crystal silicon mirror segments. This is a significant leap from Chandra's four pairs of mirror segments (NASA 2023).

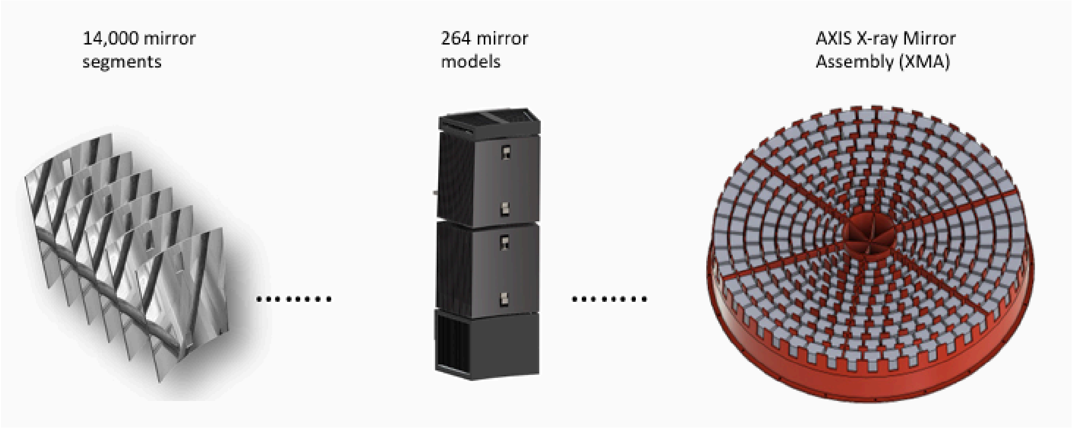

Figure 2. The major steps of the assembly. Left: production and qualification of approximately 14,000 mirror segments; Middle: Alignment and integration of these mirror segments into 264 mirror modules, and Right: the mirror modules are assembled into the final AXIS assembly shown here integrated into the "spider" structure (Reynolds et al. 2023).

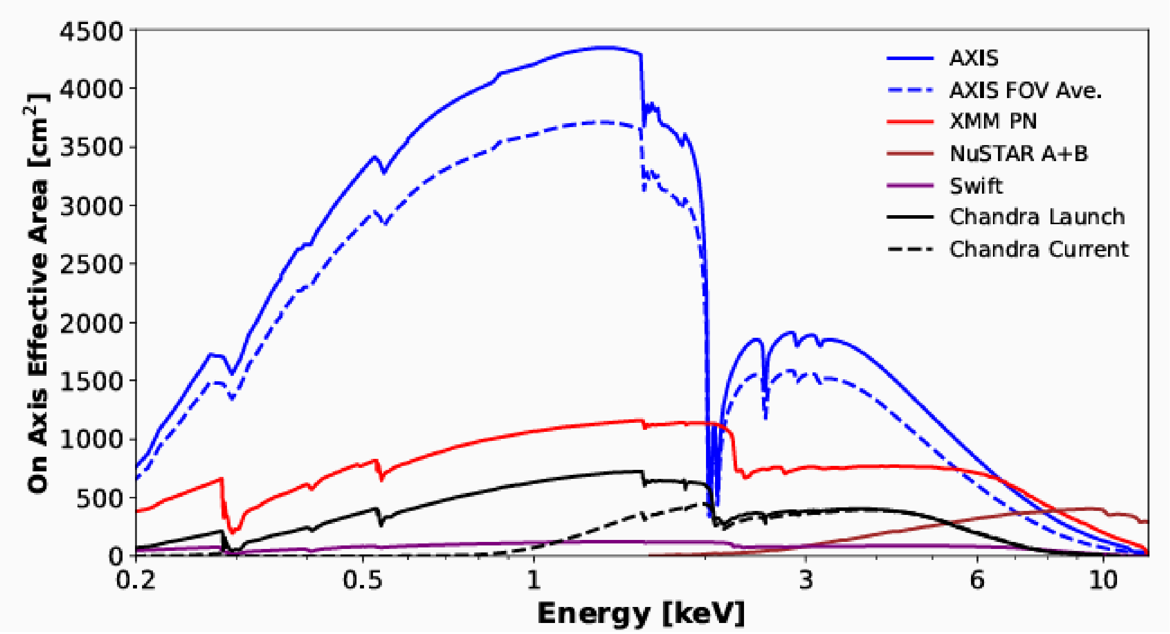

Figure 3. Mirror effective area for AXIS (blue) compared to XMM-PN (red), NuSTAR (A and B

telescopes combined; brown), CXO at launch (black) and CXO in 2023 and hence affected by contamination buildup (dashed) (Reynolds et al. 2023).

Aims of research on this subject include better understanding how these cavities evolve over time, becoming better equipped to determine the point at which this bubbling phenomenon began in the universe, and evaluating the potential performance of AXIS at higher redshifts than its predecessors could reliably make observations. Measurements of cavities can also lead to insight about the power output of the jets. Another issue is that Rayleigh-Taylor and Richtmyer-Meshkov instabilities are expected to grow on the top of the cavity, and Kelvin-Helmholtz instabilities are observed to develop on the shear flow at the sides of the cavity as it rises. However, bubbles with rise times that are on the order of several times the predicted instability timescales have been observed, making this explanation uncertain. It is thought, then, that something has to limit the growth of these instabilities (Diehl et al. 2008). Physical factors such as tangential magnetic fields (Jones & De Young 2005), viscosity (Reynolds et al. 2005), or continuous inflation of the bubble (Pizzolato et al. 2006) have been proposed to explain the diminished influence of these instabilities. This topic could be better studied with observations of farther-out cavities, which AXIS would contribute to.

Methods

The first stage required using ‘sim_cav_4.pro’ to create an image of two cavities rising from an AGN. This simulation has five user inputs: the distance of the cavity from the center, the radius of the cavity, the number of pixels, the number of runs, and the indicator of the random value generator. We focused on varying the former three parameters. It starts by dividing a data cube into *n* number of pixels. Each block contains information about the gas density, which is proportional to the x-ray emission, squared. The two spherical cavities have emission set to 0, meaning they are modeled as having no gas inside.

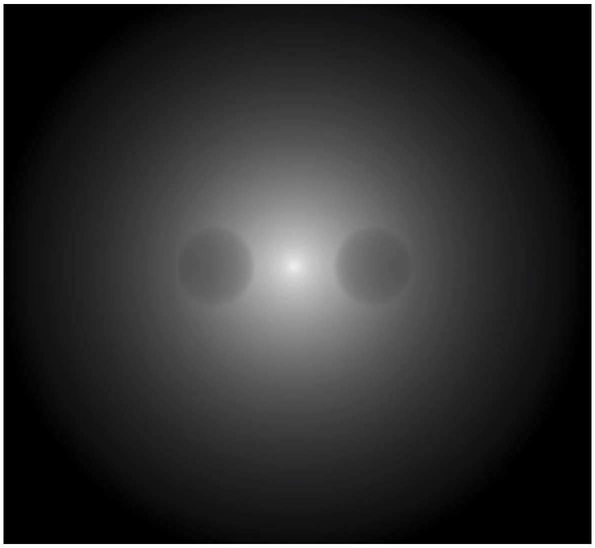

Figure 4. Simulated image of AGN-inflated bubbles created in DS9 on a linear scale.

Next, that output, an example of which is fig.4, is input into SIMX, which simulates the response of photon-counting detectors aboard potential future missions, including AXIS. SIMX has many input parameters, but the values of interest we varied were the exposure time, source flux, and image file (output from sim_cav_4).

- Exposure time: This input corresponds to the time, in seconds, that AXIS observed the source. This value was generally kept to a minimum to be consistent with real-world protocols.
- Source Flux: This input corresponds to the source flux of the target in erg $s^{-1}cm^{-2}$. This value was varied by using different redshifts, and based on the luminosity value of the Perseaus galaxy cluster, which is $5x10^{44}$ erg/s.

★ Source image: This input was filled by the corresponding output from sim_cav_4.

The source flux values for each redshift we investigated can be found in table 1, and were calculated using equation 1.

Redshift (z)	Source Flux (erg $s^{-1}cm^{-2}$)
0.6	$3.28x10^{-13}$
0.8	$1.62x10^{-13}$
1.0	$9.30x10^{-14}$
1.2	$5.91x10^{-14}$
1.4	$4.04x10^{-14}$
1.6	$2.89x10^{-14}$
1.8	$2.16x10^{-14}$

Table 1. Calculated values of source flux for each redshift of interest using Equation 1, where L is the luminosity, D_L is the luminosity distance, and F is the source flux.

$$L/4\pi D_L^2 = F \tag{1}$$

The image produced by SIMX is then visualized in DS9. A projection is used to collect data on the source count across a region of the cavity, then compared to that of a region without a cavity. For smaller targets, a box projection was used, and for larger targets, pie and annulus (PANDA) projections were used. This is because larger targets had lower source counts, particularly near the outside edges of the cavities.

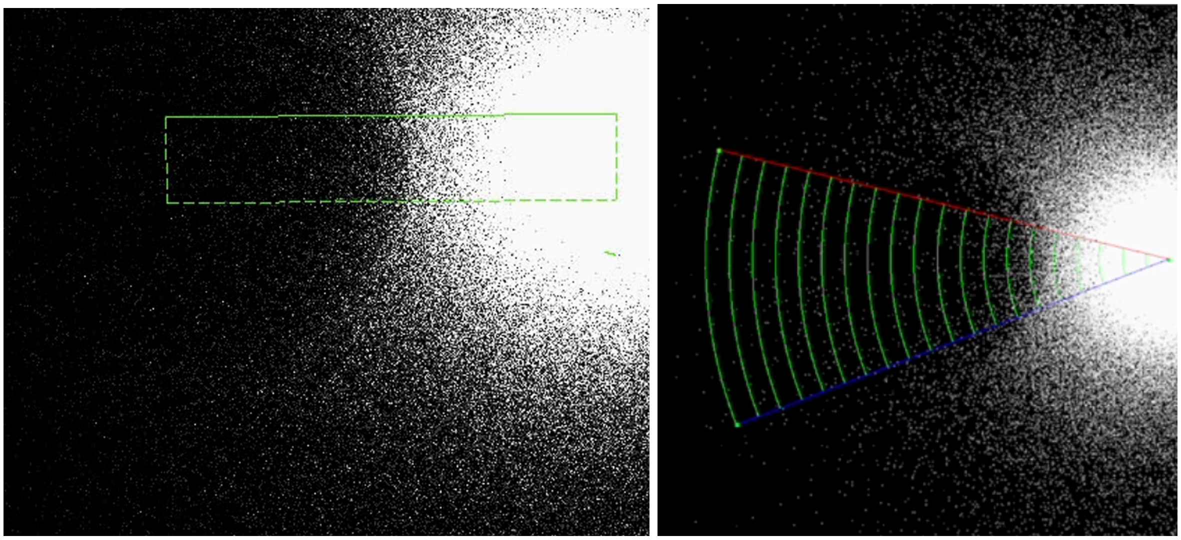

Figure 5. Example of using a projection in DS9 to collect data from SIMX outputs. Left: box projection, right: PANDA projection.

Results

Surface brightness profiles were made from the projection data, as seen in figs. 6 and 7.

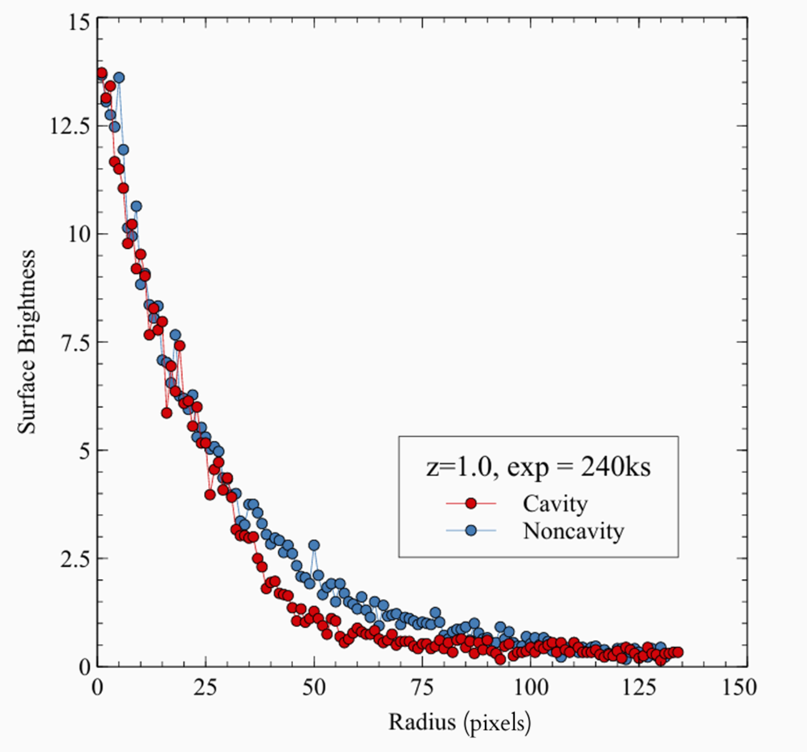

Figure 6. Surface brightness profiles for a cluster at a redshift of 1.0, as visualized with SIMX using an exposure time of 240 ks. Surface brightness is a measure of the number of protons detected per square arcsecond.

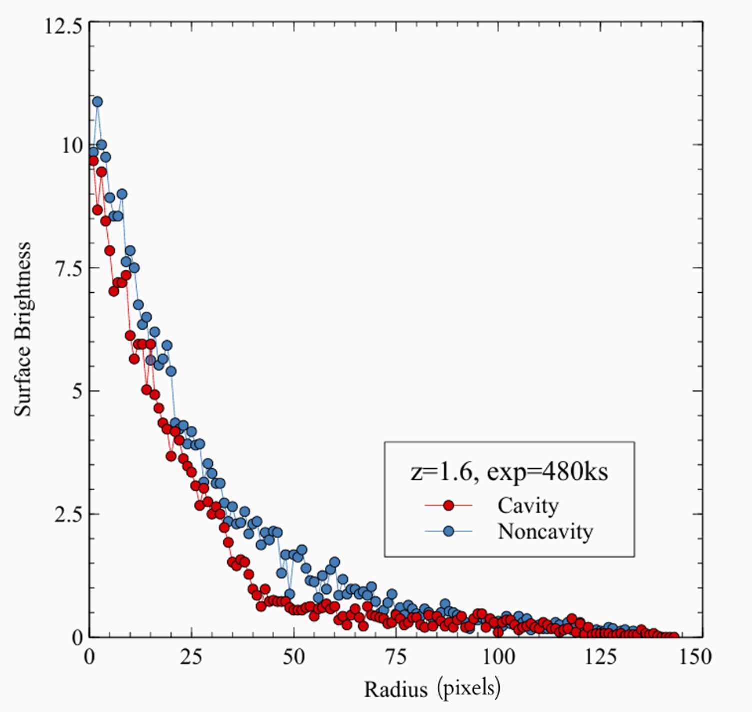

Figure 7. Surface brightness profiles for a cluster at a redshift of 1.6, as visualized with SIMX using an exposure time of 480 ks. Surface brightness is a measure of the number of protons detected per square arcsecond.

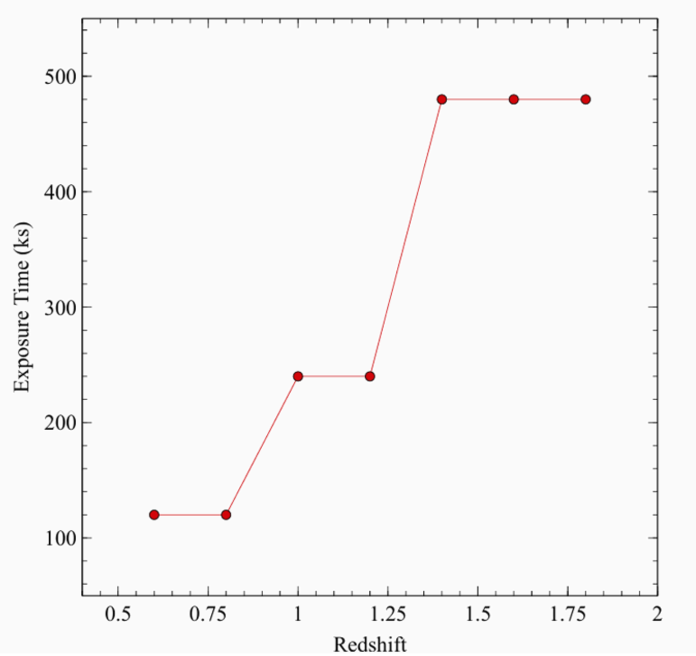

Figure 8. Minimum exposure time VS redshift of the cluster

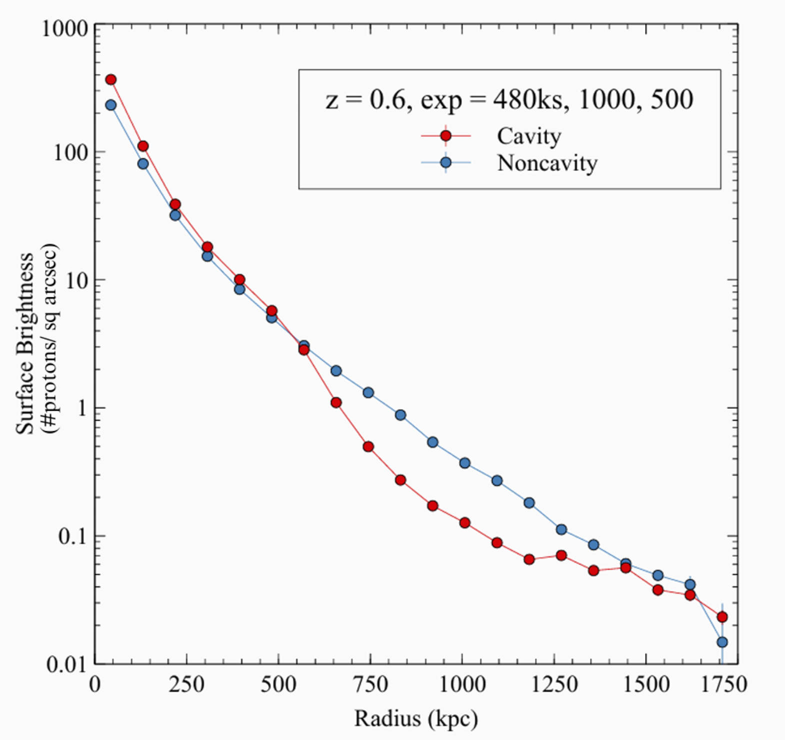

Figure 9. Surface brightness profiles on a log scale for a cluster at a redshift of 0.6, as visualized with SIMX using an exposure time of 480 ks. The radius and distance of the cavities are 500 and 1,000 kpc, respectively.

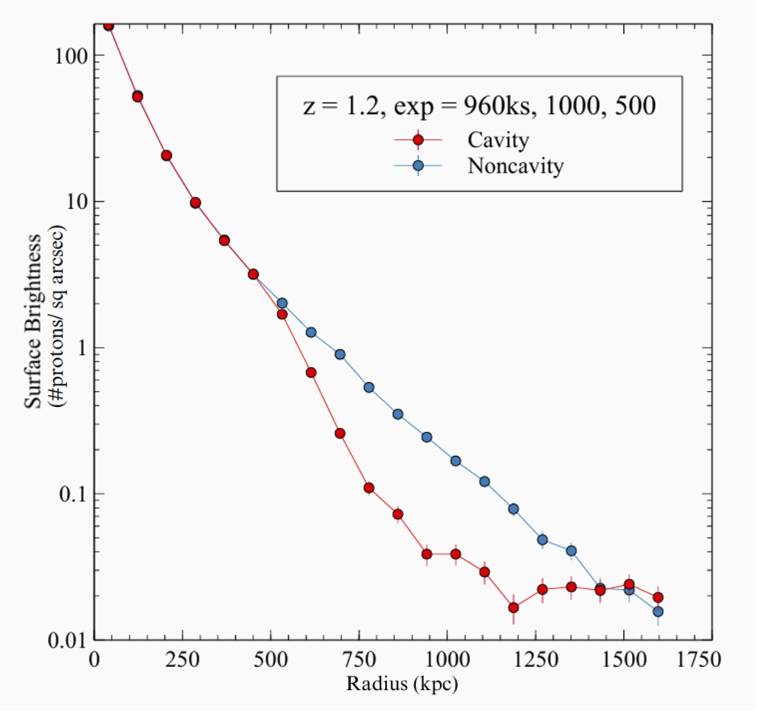

Figure 10. Surface brightness profiles on a log scale for a cluster at a redshift of 1.2, as visualized with SIMX using an exposure time of 960 ks. The radius and distance of the cavities are 500 and 1,000 kpc, respectively.

Conclusions

The results of this study are promising for the outlook of the performance of AXIS. An important result can be seen in figures 9 and 10, where the gap between the curves indicates dimming due to a cavity. The length of each of these openings is ~1000 kpc, which agrees well with our input value of a cavity with a radius of 500 kpc. Therefore, it is reasonable to believe we may be able to accurately determine the size of cavities at this scale with AXIS under the right conditions. Additionally, the exposure times required for these observations is an achievable value relative to current X-ray observations.

Future work

A similar analysis can be done with simulated cavities with different shapes (more ellipsoidal) and orientations compared to the line-of-sight angle of 90^o used here. Further testing can also be done to verify results with different input values and other initial conditions. It is not yet known if AXIS will become fully developed, but it would undoubtedly be invaluable to many applications of X-ray astronomy.

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