The First Astrophysical Result of Hisaki: A Search for the EUV He Lines in a Massive Cool Core Cluster at $z = 0.7$

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Abstract

Molecular cold gas and star formation have been observed at centers of cool core clusters, albeit at a level much smaller than expected from the classic cooling model. Feedback from the supermassive black hole is likely to have prevented hot gas from cooling. However, the exact cooling and heating processes are poorly understood. The missing key piece is the link between the hot gas ($10^7$ K) and cold gas ($10^3$ K). Using the extreme ultraviolet spectrometer on board Hisaki, we explore a distant galaxy cluster, RCS2 J232727.6-020437, one of the most massive cool core clusters with a cooling rate of $400 M_\odot yr^{-1}$. We aim to detect gas at intermediate temperatures ($3 \times 10^4$ K) emitting HeI $\alpha$ and HeI $\beta$ at rest wavelengths of 58.4 nm and 53.7 nm, respectively. Our target resides at $z = 0.6986$, for which these HeI lines shift away from the absorption of the Galaxy. Our findings show that the amount of $10^{4-5}$ K gas at the center of this cluster is smaller than expected if cooling there was uninhibited, which demonstrates that feedback both operates and is efficient for massive clusters at these epochs.

Key words: galaxies: clusters: intracluster medium

1. Introduction

X-ray surface brightness increases rapidly toward the center of cool core clusters (Forman & Jones 1982). At the densities and temperatures observed in these regions, the X-ray emitting gas can cool catastrophically within a time much shorter than the Hubble time. The classic cooling flow model predicts star formation rates of a few $100 M_\odot yr^{-1}$ fueled by the condensation of the X-ray emitting hot gas. In contrast, the observed star formation rates are typically below $10 M_\odot yr^{-1}$ (e.g., O’Dea et al. 2008). To reconcile the discrepancy, energy released by the active galactic nuclei (AGNs) is invoked to compensate for the loss from the radiative cooling (McNamara & Nulsen 2007). Cooling and heating are continuous processes. The entire feedback loop could be mapped out best if we knew the distribution of gas at all temperatures between the hottest ($\sim 3 \times 10^7$ K) and coolest ($\sim 30$ K) phases. High-resolution X-ray spectroscopy of XMM-Newton-RGS puts upper limits on the amount of $10^4$ K gas via the observations of the Fe XVII line emission (e.g., Peterson et al. 2003). Far-Ultraviolet Spectroscopic Explorer (FUSE) UV observations of the O VI line have probed the bulk of gas at $10^5$ K (Oegerle et al. 2001; Bregman et al. 2006). These studies suggest that gas at intermediate temperatures is deficient relative to the expectations of radiative cooling models.

We present the first line emission observations of HeI $\alpha$ at rest wavelengths of 58.43 nm and HeI $\beta$ at 53.70 nm from a cool core cluster, seeking for gas at $10^{4-5}$ K. HeI $\alpha$ and HeI $\beta$ lines have long been predicted in the atomic database (Dere et al. 1997; Landi et al. 2013; Ferland et al. 2017). The measurements of these neutral helium lines in intergalactic clouds using high redshift quasars can reveal the helium abundance in the early universe, putting unique constraints on big bang nucleosynthesis (Reimers & Vogel 1993; McQuinn & Switzer 2010). HeI $\alpha$ and HeI $\beta$ lines have also been studied extensively in the solar plasma (Golding et al. 2017), i.e., providing strong diagnostics of motions in prominences (Labrosse et al. 2007). HeI $\alpha$ and HeI $\beta$, which both peaked at a temperature of $3.16 \times 10^4$ K, are ideal tracers of gas at intermediate temperatures. In the intracluster medium (ICM), helium is much more abundant than iron and oxygen. Despite the rich physics they can probe, these neutral helium lines have never been studied in clusters of galaxies. For nearby clusters, the wavelengths of HeI $\alpha$ and HeI $\beta$ lie short-ward of the Lyman edge. Galactic absorption would reduce the line flux by 3–4 orders of magnitude, making them effectively undetectable. Our target RCS2 J232727.6-020437 (hereafter RCS2327) is a galaxy cluster residing at $z = 0.6986$, for which the wavelengths of HeI $\alpha$ and HeI $\beta$ have shifted to 99.25 nm and 91.21 nm, respectively, long-ward of the Lyman edge.

Hisaki is a Spectroscopic Planet Observatory operated by JAXA. It was launched in 2013 as the first mission of the Small Scientific Satellite Project (Yoshikawa et al. 2013). Its EUV spectrometer produces a two-dimensional spectral image over the wavelength of 55–145 nm (Yoshikawa et al. 2014; Kimura et al. 2019). Hisaki observations are limited to targets with latitudes within $\pm 10^\circ$ in the Ecliptic Coordinate. Over the past few years, Sunyaev–Zel’dovich (SZ; Sunyaev & Zel’dovich 1972) surveys (i.e., Planck, SPT, ACT) have discovered a rapidly growing number of distant clusters. We searched through galaxy clusters in the SZ Cluster Database7 and found four clusters at $z \geq 0.7$ that are visible to Hisaki. Among them, RCS2327 is the only cool core cluster. RCS2327 was first discovered in the Second Red-Sequence Cluster Survey (RCS2; Gilbank et al. 2011). It is one of the most relaxed
and spherically symmetric clusters. Sharon et al. (2015) have measured its total mass in every known way: hydrostatic X-ray measurement, weak-lensing, strong-lensing, SZ effect, dynamics of member galaxies, and galaxy richness. The authors found that all these methods give consistent results that RCS2327 is the most massive galaxy cluster at this redshift with an enclosed mass of $3 \times 10^{15} M_{\odot}$ within its virial radius ($R_{200} = 2.1 \text{ Mpc}$).

We present joint Hisaki EUV and Chandra X-ray observations of RCS2 J232727.6-020437. We adopt the cosmological parameters $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.73$, and $\Omega_{\Lambda} = 0.27$. This cosmology gives a linear scale of 1″ = 7.24 kpc at the cluster redshift of $z = 0.6986$. Uncertainties reported are quoted at a confidence level of 68% throughout this work.

2. Observations and Data Reductions

2.1. Hisaki

Hisaki made three observations of RCS2327 in 2015 August and September. All the observations were taken during orbital night with a total exposure time of 84.4 ks. A slit width of 60″ was used, which gives a spectral resolution of $\lesssim 10$ Å and a spatial resolution of $\lesssim 17$ ″. Only Level 2 data were included in our analysis. Data reduction was performed with the IDL Astronomy User’s Library and NAIF SPICE toolkit. A spectral image integrated over all observations is shown in Figure 1. The Hisaki detector extends over the full angular range ($−1000″$, 600″), but only the region in the range ($−180″$, 180″) is exposed to the sky. We extract instrumental background from the range (200″, 300″). Our target is centered at 110″. A spectrum of RCS2327 over (100″, 120″) with instrumental background subtracted is shown in Figure 2. No obvious emissions are detected other than geocoronal emission lines (Kuwabara et al. 2017).

The sky background is not uniformly distributed over the field of view of Hisaki. This is critical for faint sources like our target. We calibrate the spatial variation of the local background based on the distribution of geocoronal emission lines. The Hα line around 80 nm is a ghost line and should be ignored. The spatial distribution of the Lyα line has been severely affected by the dumbbell slit mode for Jupiter monitoring. Therefore we only consider geocoronal emission lines of Lyman $\beta$ (102.5 nm), O II (83.4 nm), O I (130.4 nm), and He I (58.4 nm). We obtain the total flux of these four lines (with a spectral bin size of 1 nm) as a function of viewing angle: $f_{\text{geo}}(\theta)$. We normalize the flux of He Iα and He I β as a function of viewing angle by $f_{\text{geo}}(\theta)$. We extract the signal spectrum from 100″ $\sim$ 120″, corresponding to a region centered on the cluster X-ray peak with a radius of 74 kpc. We extract a local background from $−120″$ $\sim$ $−100″$, which consists of both astrophysical and instrumental backgrounds. The resulting background subtracted spectrum zoomed in on He Iα and He I β is shown in Figure 3.

2.2. Chandra

We use the Chandra X-ray Observatory to probe the ICM properties of RCS2327. The superb spatial resolution of Chandra makes it ideal to study this cluster at high redshifts. Our analysis includes all three Chandra observations of RCS2327: one 25 ks ACIS-S pointing (ObsID: 7355) taken in 2007 August and two $\sim 75$ ks ACIS-I pointings (ObsID: 14025 and 14361) obtained in 2011. CIAO 4.8 and CALDB 4.6.9 were used for the data reduction, chandra_repro was used to reprocess all the observations from level 1 events. Background flares beyond 3$\sigma$ were filtered using the light-curve filtering script lc_clean. We obtain a total of 166 ks cleaned exposure times. Point sources were detected in a 0.3–7.0 keV image with wavdetect. A mosaic image of RCS2327 is shown in Figure 4; its X-ray morphology is
symmetric with no significant substructures detected in the ICM, suggesting that RCS2327 is a relaxed cluster. We extract spectra from five consecutive annuli centered on the cluster center as shown in Figure 4, so that each annulus contains at least 5000 net counts. The innermost region has a radius of 61 kpc ($8'$). Tailored blank sky spectra generated with the CIAO tool blanksky were applied as the background spectra. All spectra were grouped to have at least one count per energy bin. Spectral fitting was performed with XSPEC 12.9.1 using the C-statistic. Deprojection was performed by fitting the spectra with the mixed model: $\text{proj} \times (\text{phabs} \times \text{vapec})$. The solar abundance standard of Asplund et al. (2006) and a Galactic hydrogen column of $N_H = 4.8 \times 10^{20} \text{cm}^{-2}$ (Kalberla et al. 2005) are adopted.

### 3. Results

#### 3.1. He I Line Emission

We present the Hisaki spectrum of the central $r < 74 \text{kpc}$ of RCS2327 in Figure 2, corresponding to $(100'' \sim 120'')$ on the detector. A zoomed-in view of He I$\alpha$ and He I$\beta$ is presented in Figure 3 with local background $(-120'' \sim -100'')$ subtracted. Their fluxes are consistent with a nondetection. The absence of He I$\alpha$ and He I$\beta$ line emissions is unexpected in a steady...
cooling flow scenario in which X-ray emitting gas cools at an estimated cooling rate of hundreds of solar mass per year. However, their upper limits still allow some level of cooling that we will discuss in Section 4.

The systematic uncertainties are dominated by the spatial variation of the instrumental backgrounds and the airglow foregrounds. To access the systematic uncertainties, we repeat the analysis by using each of the following 40 regions as the local background:

\[ -120\arcsec \sim -100\arcsec, -100\arcsec \sim -80\arcsec, ... 100\arcsec \sim 120\arcsec . \]

The resulting flux of He Iα and He Iβ are shown in Figure 5. We fit their flux distributions to a skew-normal model. We take the standard deviation of the flux distribution as the systematic uncertainty. The measured fluxes of He Iα and He Iβ are

\[ -6.9 \pm 3.1 \text{ (sta) } \pm 7.0 \text{ (sys)} \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \] and

\[ 1.3 \pm 3.2 \text{ (sta) } \pm 5.1 \text{ (sys)} \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}, \]

respectively.

### 3.2. X-Ray Emitting ICM

We performed a deprojected analysis of the hot gas in RCS2327 using Chandra observations as shown in Figure 6. The best-fit temperature is 8 keV at the cluster center and increases to 14 keV at 300 kpc (\( \sim 0.15 R_{\text{vir}} \)). We calculate the gas cooling time, \( t_{\text{cool}} \), using

\[
 t_{\text{cool}} = \frac{3P}{2n_e n_H \Lambda(T, Z)},
\]

where \( P = 1.8n_e kT \) is the pressure and \( \Lambda(T, Z) \) is the cooling function determined by the plasma temperature and metallicity. The three-dimensional entropy profile is derived with the temperature and density profiles, \( K = kT n_e^{-2/3} \). Numerical simulations and observations of high redshift clusters suggest that most massive clusters have assembled around \( z = 2 \) (Chiang et al. 2013; Wang et al. 2016). At the current redshift of RCS2327, 4 Gyr has passed since its formation. Only the innermost bin has a cooling time shorter than 4 Gyr, defining the regime of the cool core. A central metallicity excess, probably produced by supernova explosions in the brightest cluster galaxy, is also typical for relaxed cool core clusters. The innermost bin of our analysis has a metallicity of 0.6 \( Z_\odot \), while the outer region displays a more uniformly distributed metallicity of 0.3 \( Z_\odot \), although the existing data is not deep enough to indicate a significant central metallicity excess. We
calculate the cooling rate via

\[ M_{\text{cool}} = \frac{2 \mu m_p L_X}{5 k T X} \]  

(2)

where \( L_X \) is the bolometric X-ray luminosity and \( \mu = 0.62 \) is the mean molecular weight. Its cooling rate, integrated over the cool core, is \( M_{\text{cool}} = 411 M_\odot \text{yr}^{-1} \), indicating a strong cooling flow.

4. Discussion

We have performed the first EUV observation of a galaxy cluster using the Hisaki Planetary Observatory. This is Hisaki’s first observation of an astrophysical object. We aim to probe gas at \( 10^{4-5} \) K via measuring the flux of He I lines. Our target RCS2327 resides at \( z = 0.7 \). The wavelengths of He I and He I/β are redshifted to 99.25 nm and 91.21 nm, respectively. These wavelengths are in the range of Hisaki and long-wand of the Lyman edge of the Galaxy. RCS2327 is one of the most massive and relaxed clusters in the universe. The innermost region in our Chandra analysis has \( r \) radius of 61 kpc. Its deprojected entropy index is \( 80 \) keV cm\(^2\) and its cooling time is \( 2.4 \) Gyr. Typical nearby cool core clusters have an entropy as low as \( 10 \) keV cm\(^2\) and a cooling time of \( \sim 1 \) Gyr within \( r < 10 \) kpc (Panagoulia et al. 2014). We fit the entropy profile to a power-law model and obtain a best-fit slope of \( 0.94 \pm 0.07 \). Extrapolating this best-fit profile to the inner \( 10 \) kpc, its entropy would reach below \( 20 \) keV cm\(^2\). The surface brightness within the innermost \( b \) keeps rising toward the cluster center as shown in Figure 7. The actual cooling at the cluster center is likely to be more vigorous than what we could infer spectroscopically with existing Chandra data.

4.1. Gas Mass at Intermediate Temperatures

The flux of He I lines allows us to probe its cluster gas at \( \sim 3 \times 10^4 \) K. The upper limit of the He I/β line is substantially higher than that of the He I α line (Section 3.1). Therefore, we use the measurement of the He I/β line to put upper limits on the mass and volume of the gas at intermediate temperatures at the center of RCS2327. We calculate \( \Lambda_{\text{cool}} \cdot n_{H_1} \), the energy loss rate per unit volume, where \( \Lambda_{\text{cool}} \) is the contribution to the cooling function from each line and the ratio of \( n_e \) to \( n_{H_1} \) is 1.2. We add the statistical and systematic uncertainties in quadrature to obtain the 1σ upper limit of \( 7.8 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \) for He I/β, which requires the volume of the \( \sim 3 \times 10^4 \) K gas to be \( < 1.2 \times 10^9 \) pc\(^3\). We assume that the warm gas and the X-ray emitting hot gas are in pressure equilibrium. We obtain that the \( \sim 3 \times 10^4 \) K gas mass should be no more than \( 2.9 \times 10^9 M_\odot \). As we discuss below, gas at intermediate temperatures provides unique constraints on the interaction between the hot gas and the cold gas, particularly the direction of the energy flow. We demonstrate the implications of the lack of warm gas in RCS2327 via making analogies with the brightest galaxy cluster in X-ray, Perseus and the nearest galaxy cluster, Virgo.

4.1.1. Cooling

Gas at intermediate temperatures can be produced via the cooling of the X-ray emitting hot gas. The nearby cluster, Perseus, is the brightest galaxy cluster in X-ray (Forman et al. 1972). Its cool core has been observed extensively over the entire electromagnetic spectrum. In particular, extended filaments associated with the X-ray emitting hot gas at \( 10^4 \) K has been observed surrounding its BCG NGC 1275 (Conselice & Gallagher 1999; Gendron-Marsolais et al. 2018). Up to \( 5 \times 10^3 M_\odot \) of cold molecular gas has been found to be associated with these H\(_2\) filaments (Salomé et al. 2006). The stellar body of NGC 1275 contains blue star clusters, which is unusual for an early-type galaxy (Conselice et al. 2001). The cool core of Perseus clearly contain multiphase materials, which is not rare for nearby cool core clusters (McDonald et al. 2010). The rich phenomena in NGC 1275 may be explained by the residual cooling coupled with the mechanical feedback of its AGN (Salomé et al. 2006).

We note that the cool core of the Perseus cluster has an X-ray-derived mass deposition rate of \( M_{\text{cool}} = 300 M_\odot \text{yr}^{-1} \) (Fabian et al. 2000), which is comparable to that of RCS2327 of \( 400 M_\odot \text{yr}^{-1} \). If Perseus were like RCS2327 with little warm gas at \( 3 \times 10^4 \) K, it would undermine the role of the cooling of X-ray emitting hot gas; instead, recent mergers with gas-rich galaxies may be invoked to interpret the multiphase cluster gas (Conselice et al. 2001).

4.1.2. Conduction

We estimate that the volume of the \( \sim 3 \times 10^4 \) K gas is no more than \( 1.2 \times 10^9 \) pc\(^3\) in RCS2327. If such warm gas is distributed throughout the cool core, it would have an extremely small volume filling factor \( (f < 10^{-6}) \). The upper limit we obtain allows it to exclusively occupy individual filaments (i.e., with a radius of \( r_c < 100 \) pc). Any warm gas in RCS2327 is likely to be confined in filament structures. Using Hubble Space Telescope/Cosmic Origins Spectrograph observations, Anderson & Sunyaev (2018) studied FUV emission along the line of sight to a filament in M87, the BCG of the Virgo cluster. The authors infer that warm gas \( (T \sim 10^5 \text{ K}, n \sim 10 \text{ cm}^{-3}) \) forms a thin layer around cold filaments \( (T \sim 10^3 \text{ K}, n \sim 1000 \text{ cm}^{-3}) \), which are imbedded in the hot ICM \( (T \sim 10^7 \text{ K}, n \sim 0.1 \text{ cm}^{-3}) \). If the constraints we put on the \( 3 \times 10^4 \text{ K} \) gas \( (n \lesssim 100 \text{ cm}^{-3}) \) can be applied to the filament in M87, the \( 3 \times 10^4 \text{ K} \) gas may form a third layer between the \( T \sim 10^5 \text{ K} \) gas and the cold clumps. A possible structure of the multiphase filament is demonstrated in Figure 8. Cold gas evaporating through conductive heating would be a natural explanation of these multiphase gases that
are in pressure equilibrium. The lack of warm gas would otherwise suggest quenched conduction.

### 4.1.3. Mixing

Cold gas could flow through the ambient hot gas to reach the supermassive black hole. A highly turbulent ICM would promote Kelvin–Helmholtz instability to develop at the interface to form a layer of mixed gas (Begelman & Fabian 1990; Su et al. 2017a, 2017b). The expected gas temperature resulting from the mixing between the $10^5$ K cold gas and the $10^7$ K hot gas should be approximately $\sqrt{T_c T_h} = 10^5$ K (Fabian et al. 2001). If the turbulent mixing is effective, the $10^5$ K gas may overshadow gas at higher or lower temperatures (Fabian et al. 2001; Oegerle et al. 2001). This scenario is consistent with previous observations and our results: FUSE has speculatively detected gas near $10^5$ K in cool core clusters: O VI emission at $3 \times 10^5$ K and C III emission at $7 \times 10^4$ K in A2597 (Oegerle et al. 2001) and possibly also in A1795 (Bregman et al. 2006). The XMM-Newton RGS spectra of A1835 indicates a lack of Fe XVII emission at $4 \times 10^5$ K (Peterson et al. 2003) and our study reveals a nondetection of He I lines at $3 \times 10^4$ K in RCS2327. Hitomi observations of the Perseus Cluster, however, indicate a rather quiescent ICM with a turbulent velocity of $\sim 150$ km s$^{-1}$ (Hitomi Collaboration et al. 2016). Yet the existing UV-EUV observations and the Hitomi observations are too few and none of these observations are performed for the same cluster.

### 4.2. Steady Cooling Flow

We expect emission lines to be produced by the cooling plasma. We calculate the expected line emission luminosities of He I$\alpha$ and He I$\beta$ following Edgar & Chevalier (1986),

$$L_{\text{line}} = \frac{k}{\mu m_H} A_Z \int_{T_{\text{min}}}^{T_{\text{max}}} \left( \frac{3}{2} + \frac{s}{2} \right) \frac{f_i \lambda_{\text{line}}}{\Delta} \frac{h c}{\lambda_{\text{line}}} dT,$$

(3)

where $T_{\text{min}} = 10^4$ K and $T_{\text{max}} = 10^6$ K, $M_{\text{cool}}$ is the cooling rate (see Section 3), $A_Z$ is the abundance of He relative to H, and $\chi$ is the number of particles per H atom. The cooling process may be in an intermediate state between isobaric ($s = 1$) and isochoric ($s = 0$); therefore, we choose $s = 0.5$. The ionization fraction, $f_i (T)$, and the line emissivity coefficient, $\lambda_{\text{line}}$, are derived from AtomDB. Substituting the cool core parameters of RCS2327, we obtain an expected flux of $3.67 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and $3.85 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ for He I$\alpha$ and He I$\beta$, respectively. The expected flux of He I$\alpha$ is 10 times that of He I$\beta$. The line emission of He I$\alpha$ is not detected by Hisaki with a flux of $-6.9 \pm 3.1$ (sta) $\times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, suggesting a lack of steady cooling flow in RCS2327. However, after adding the statistical and systematic uncertainties in quadrature, we obtain a $1\sigma$ upper limit of $7.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for He I$\alpha$. Therefore, we cannot firmly rule out the cooling flow in a steady state in RCS2327. The uncertainty of the He I$\beta$ flux is too significant to provide meaningful constraints on the cooling process.

### 4.3. Thermally Unstable Cooling

Reservoirs of cold gas detected at centers of cool core clusters cast new light on the fueling of supermassive black holes (Edge 2001; Russell et al. 2014, 2016, 2017; Vantyghem et al. 2016; McNamara et al. 2016). The prevailing AGN feedback model suggests that thermal instability can happen if the ratio of the cooling time $t_{\text{cool}}$ and the freefall time $t_{ff} = (\frac{\sqrt{2r/g}}{r})$ drops below a threshold value (McCourt et al. 2012). Cold gas, condensed from the hot gas, could be accreted onto the supermassive black hole to trigger AGN feedback (Gaspari et al. 2013). Massive galaxy clusters that do contain cold gas seem to have a $t_{\text{cool}}/t_{ff}$ ratio $\lesssim 20$ (Hogan et al. 2017). We present the $t_{\text{cool}}/t_{ff}$ profile of RCS2327 in Figure 6. The total mass profile taken from Sharon et al. (2015) was used to compute the gravitational constant $g$. The measured values of $t_{\text{cool}}/t_{ff}$ in the central region of RCS2327 are consistent with values below 20. The absence of gas at intermediate temperatures implies that there may be a delay between the drop of $t_{\text{cool}}/t_{ff}$ and the onset of the thermal instability. Then again, the uncertainty of its $t_{\text{cool}}/t_{ff}$ is too significant and its cold gas content is unknown; RCS2327 may not satisfy the condition to induce thermal instabilities.

### 5. Summary

This work presents the first measurement of He I lines at the center of a cool core galaxy cluster, probing cluster gas at $10^{4.5}$ K. Our target, RCS2 J232727.6-020437, is a massive cluster at $z = 0.7$, placing its redshifted He I lines long-ward of the Lyman edge at $z = 0$. Currently, there are no active instruments intended for extragalactic EUV studies. The EUV observations used in this study were performed with the Hisaki Planet Observatory. We put upper limits on the He I$\alpha$ and He I$\beta$ line emission. The mass of the $3 \times 10^4$ K gas is no more than $2.9 \times 10^8 M_\odot$, occupying a volume of $<1.2 \times 10^8$ pc$^3$. Any such warm gas is likely to be confined to filament structures rather than extending throughout the cool core. Our nondetection of the $10^{4.5}$ K gas suggests that the steady radiative cooling is suppressed, although the substantial systematic uncertainty does not allow us to firmly rule out the cooling flow model.
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