

Micro-Calorimeter X-Ray Spectroscopy of Galaxy Clusters using the XRISM X-Ray Observatory

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Julian Meunier was the sole author of Chapters 1, 2, and 6, written under the supervision of Dr. Brian R. McNamara and not written for publication.

This thesis contains in part of four manuscripts written for publication. Exceptions to sole authorship of material are as follows:

Chapter 3

Section 3.2.1 was analyzed and written by I, Julian Meunier, to summarize my contributions to the analysis and discussion of the published manuscript XRISM Collaboration 2025 ([133]). Section 3.3.1, written by I, Julian Meunier, uses some of the analysis and concepts used in the published manuscript, but does not contain material written for publication. The analysis was led by the corresponding authors of the published manuscript Irina Zhuravleva, Congyao Zhang, and Annie Heinrich. The remaining authors are my supervisor, Brian R. McNamara, and collaborators that provided some of the processed spectra, RMFs, and ARFs, the cropped Chandra source image, as well as contributed to the analysis and provided comments on how to improve the manuscript before submission for publication.

Sections 3.1 and 3.2.2–3.4, except section 3.3.1, are presented in J. Meunier et al., in Prep. ([84]), which is undergoing edits and is expected to be submitted for publication in a future journal. In this manuscript, I, Julian Meunier, am the main author, having analyzed the data and written the manuscript. The secondary author, Brian R. McNamara, is my supervisor and significantly edited the relevant sections. The remaining authors are collaborators that provided some of the processed spectra, RMFs, and ARFs, a custom Xspec model, the cropped Chandra source image, as well as provided feedback for the analyses and comments on how to improve the manuscript before submission for publication.

Chapter 4

Chapter 4 contains contributions to the published manuscript T. Rose et al., 2025 ([103]). In this manuscript, I, Julian Meunier, am the third author, having analyzed the data with the main author and provided some edits to the manuscript. The main author, Tom Rose, analyzed the data and wrote the manuscript. The secondary author, Brian R. McNamara, is my supervisor and significantly edited the manuscript. The remaining

authors are collaborators that provided comments on how to improve the manuscript before submission for publication.

Chapter 5

Chapter 5 contains contributions to the manuscript A. Majumder et al., 2025 in Press ([76]), which is awaiting publication. In this manuscript, I, Julian Meunier, am the third author, having analyzed the data with the main author. The main author, Anwesh Majumder, analyzed the data and wrote the manuscript. The remaining authors are my supervisor, Brian R. McNamara, and collaborators that provided comments on how to improve the manuscript before submission for publication.

Abstract

Galaxy clusters are some of the most massive objects in the universe, yet the evolution of these objects, particularly with regards to the heating and cooling of the intracluster medium, still has many unknowns. With the launch of the new X-ray imaging and spectroscopy mission, XRISM, galaxy clusters can now be studied with higher precision. This data can reveal a plethora of new information about the dynamics of the atmospheres of these clusters, which can be used to develop a better understanding of the evolution of galaxy clusters.

In this thesis, I present analysis of X-ray spectroscopic data of the Perseus, Hydra A, and Cygnus A clusters obtained with XRISM Resolve. We apply spectral modeling techniques to the data to derive gas temperature, metal abundance, velocity dispersion, and bulk velocity to develop a further understanding of the dynamics of the intracluster medium in these galaxy clusters.

I present spectral analysis of the five XRISM Resolve pointings of the Perseus cluster, binned into a radial profile. We measure radial profiles of temperature, metal abundances, velocity dispersion, and bulk velocities up to ~ 250 kpc from the cluster center with single temperature models. While the temperature and abundance profiles are consistent with typical cool core clusters, the velocity dispersions suggest a relatively quiescent state for the intracluster medium, with only up to ~ 175 km s $^{-1}$ dispersion in the central ~ 60 kpc. We interpret this velocity dispersion to be due to turbulence. The dispersion profile suggests that the jets and bubbles may be driving turbulence in the core, but also that the core may be under-heated. We find evidence for a second temperature component in the inner ~ 60 kpc, that is cooler ($\sim 2 - 2.4$ keV) and has a significantly higher velocity dispersion of $\sim 300 - 400$ km s $^{-1}$. We interpret the cooler component to be sloshing gas from a merger or gas being churned by the jets and bubbles.

I present spectral analysis of the full-FOV XRISM Resolve data of the Hydra A cluster, measuring temperature, velocity dispersion, and bulk velocity with a single temperature model. Despite Hydra A's high jet power, we find a remarkably low velocity dispersion of 164^{+10}_{-10} km s $^{-1}$, and a small velocity offset of -37^{+20}_{-17} km s $^{-1}$ between the gas and the central galaxy. We interpret this velocity dispersion to be due to turbulence, which may suggest that the relationship between the jet power and the velocity structure of the intracluster medium is less significant than expected. However, further analysis of the outer regions of the cluster is needed to fully understand the dynamics of the gas in Hydra A.

Finally, I present spectral analysis of the full-FOV XRISM Resolve data of the Cygnus A cluster, measuring temperature, metal abundances, velocity dispersion, and bulk velocity

with a single temperature model. We measure a relatively higher velocity dispersion of 272^{+14}_{-13} km s⁻¹ with a bulk velocity of 101 ± 26 km s⁻¹ with respect to the central galaxy. These velocities likely reflect a combination of both turbulence in the gas and motion of the cocoon shock. We find some evidence for a second temperature component, that is cooler ($2.06^{+0.43}_{-0.20}$ keV) and broader (333^{+127}_{-129} km s⁻¹), with a bulk velocity of -311 ± 118 km s⁻¹. The second component may be necessary for fitting asymmetric features in the prominent emission lines of the spectrum. However, the large uncertainties of the model fit along with other uncertainties suggest that this component may not be significant.

Acknowledgements

I would like to thank my supervisor Professor Brian McNamara for the opportunity to work with him and the XRISM collaboration, allowing me to work with this exciting new data, and for providing guidance and support at every step. I thank my committee Mike Hudson and Michael Balogh for their feedback and suggestions during my presentations, and their dedication to the committee meetings and defense. I would like to thank the Perseus, Hydra A, and Cygnus A XRISM teams for allowing me to work with them, providing guidance, assistance, and technical knowledge for handling the XRISM data and software. I would like to additionally thank Neo Dizdar, Tom Rose, and Anwesh Majumder for our collaborative work with XRISM and assisting me with technical and conceptual understanding. I thank the Perseus XRISM team for providing feedback and discussion regarding the manuscript of the multiple temperature analysis of the Perseus cluster.

I would like to thank my hometown friends Elliott, Hermes, Connor, Val, Heiko, Tim, and everyone else, who have been with me for so long and supported my efforts, enjoying time together even as we spread out to all different parts of the world. I would also like to thank my undergraduate and graduate friends and colleagues, who have motivated me to strive for higher goals, had plenty of fun night outs together, and supported me and each other as we navigated through our academic lives.

Most importantly, I would like to thank my parents, who have shown me nothing but love and support throughout my entire journey, repeatedly come to visit during my time here despite being so far away, and have listened intently to my never-ending rambling about my work and astrophysics. I would also like to thank my grandparents, who have also supported me from their corners of the world, and have always done their best to be engaged with astrophysics to show their support.

Dedication

This is dedicated to my parents and grandparents. I could never have made it this far without you, and in my heart you all have contributed immeasurably to this in all the best intangible ways, so this is dedicated to you. Thank you.

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List of Abbreviations

AGN Active Galactic Nuclei [1](#), [4–7](#), [12](#), [14](#), [23](#), [25](#), [37](#), [41](#), [57](#), [60](#), [65](#), [68](#), [73](#)

ARF Auxiliary Response File [16](#), [17](#), [23](#), [25](#), [26](#), [58](#), [66](#), [68](#), [109](#)

BCG Brightest Cluster Galaxy [1](#), [4](#), [5](#), [20](#), [37](#), [57](#), [63](#), [65](#), [75](#), [77](#)

CIE Collisional Ionization Equilibrium [2](#), [18](#), [21](#), [25](#), [44](#), [58](#), [61](#), [68](#), [73](#), [75](#), [76](#)

ICM Intracluster Medium [1–5](#), [7](#), [8](#), [10–14](#), [20](#), [57–59](#), [63](#), [65](#), [68](#), [75](#), [76](#), [80](#), [81](#)

NXB Non-X-Ray Background [17](#), [58](#), [66](#), [68](#), [73](#)

RMF Redistribution Matrix File [16](#), [23](#), [25](#), [26](#), [58](#), [66](#)

SSM Spatial-Spectral Mixing [16](#), [23](#), [26](#), [60](#)

Chapter 1

Galaxy Clusters

Galaxy clusters are some of the largest and most massive gravitationally bound and virialized structures in the universe, encompassing up to $\sim 10^{15} M_{\odot}$ within several Mpc [62, 78]. Galaxy clusters are filled with a hot and dilute plasma known as the [Intracluster Medium \(ICM\)](#). Only about 15% of the cluster mass is baryonic matter, as dark matter makes up the majority of the cluster mass [93]. These objects generally have a large central elliptical galaxy, more massive than typical galaxies, in the center known as a [Brightest Cluster Galaxy \(BCG\)](#). BCGs are expected to contain supermassive black hole at their centers with masses up to $\sim 10^{10} M_{\odot}$ [71]. These black holes accrete matter and eject some of the energy back out in the form of radiation, jets, and winds. These active black holes are referred to as [Active Galactic Nuclei \(AGN\)](#).

1.1 The Intracluster Medium

The [ICM](#) accounts for up to 90% of the baryonic matter in galaxy clusters, roughly 10^{13} to $10^{14} M_{\odot}$, and the remaining 10% consists of stars in the member galaxies. [ICM](#) temperatures typically range from a few 10^7 to 10^8 K, or roughly 1 to 10 keV, heated by gravitational infall [111]. The [ICM](#) is assumed to be in hydrostatic equilibrium between the gravitational potential of the galaxy cluster and the radiation pressure of the [ICM](#). Most of the energy is emitted in the X-ray, ranging in luminosities between 10^{43} to $10^{45} \text{ erg s}^{-1}$ [78]. It serves as a vast reservoir of baryons from failed stellar formation and other baryonic processes as well as heat and remnants of stellar evolution and supermassive black hole activity.

The density of the ICM ranges from 10^{-4} cm^{-3} in the outskirts to 10^{-1} cm^{-3} in the cluster core [111]. The ICM is primarily composed of ionized H ($\sim 75\%$) and He ($\sim 24\%$), along with a mix of heavier elements that make up roughly 1% of the ICM mass [87]. The mean abundance of heavy elements in the ICM is roughly 1/3rd of the solar metallicity ($Z_{\odot}$) [4]. The abundance of heavy metals typically rises to $\sim 0.8 Z_{\odot}$ in the centers of cool core clusters, and the ratios between elements like Si, S, Ar, and Ca, and Fe are $X/\text{Fe} \sim 1$ in the center [83]. Galaxy clusters are nearly ‘closed boxes’, so the ICM acts as a historical tracer of metal enrichment from star formation and stellar evolution [78]. The metal enrichment of the ICM is thought to be due to core collapse and Type Ia supernovae. However, the Fe abundance of the ICM exceeds that of the stars in member galaxies by a factor of 2 or more, which would suggest early enrichment [4, 74].

The ICM is a hot, optically thin plasma in Collisional Ionization Equilibrium (CIE). The bright X-ray radiation of the ICM is dominated by a continuum of thermal bremsstrahlung (free-free) emission. This emission is caused by a free electron being accelerated by the Coulomb field of an ion [53]. Below temperatures of $\sim 2.5 \text{ keV}$ the continuum is populated by recombination lines from elements such as Fe, Si, and O [110]. At $\sim 6 - 7 \text{ keV}$ the continuum shape is drastically altered by a complex of highly ionized Fe lines. This collection of emission lines, along with the exponential decline in continuum emission at high temperatures, provides a strong signal and is therefore used as a focal point in X-ray spectroscopy of galaxy clusters for measuring metallicity, temperature, and velocity dispersion (e.g. [59, 103, 133]). Figure 1.1 is an example of a theoretical X-ray spectrum for XRISM Resolve, showing the recombination lines and the Fe line complex.

The continuum emissivity of thermal bremsstrahlung is given as

$$\varepsilon^{ff} = 1.4 \times 10^{-27} Z^2 n_e n_i T^{1/2} \bar{g}_B \text{ erg s}^{-1} \text{ cm}^{-3}, \quad (1.1)$$

where Z is the charge of the ion, n_e and n_i are the electron and ion number densities respectively, T is the gas temperature, and $\bar{g}_B$ is a frequency average of the velocity averaged Gaunt factor [106]. This Gaunt factor, $\bar{g}_B$, is a quantum mechanical correction factor to classical approximations of the total power emitted by a plasma through free-free emission [29]. The X-ray emissivity of the galaxy cluster is then

$$L_X = \int n_e n_H \Lambda(T, Z) dV, \quad (1.2)$$

where n_H is the hydrogen number density, and $\Lambda(T, Z)$ is the cooling function – which is a function of gas temperature T and metallicity Z – which accounts for all important physical processes that contribute to X-ray emission like those mentioned above [119].

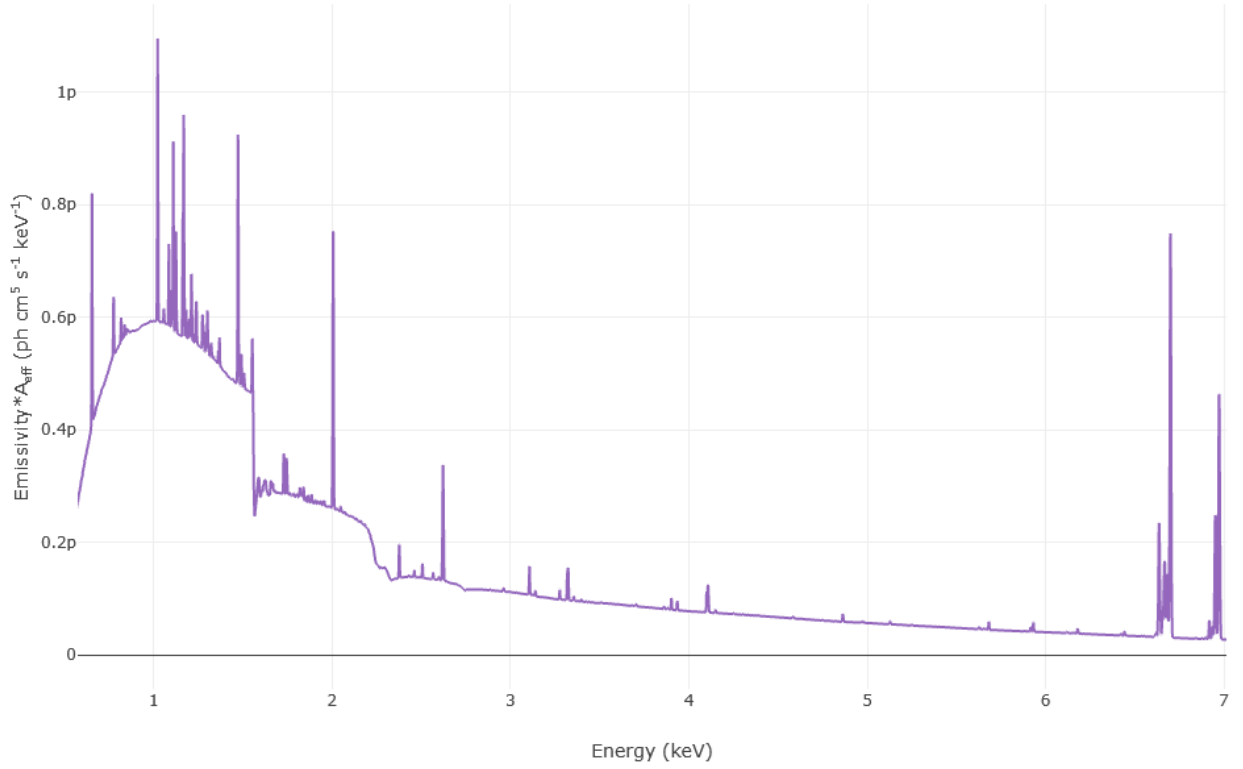


Figure 1.1: Theoretical spectrum for XRISM Resolve of solar metallicity gas at 10^8 K over the 0.5–7 keV band. Generated by `AtomDB` [47].

1.2 Cool Core Clusters

Galaxy clusters are categorized under two main classes, cool core and non-cool core clusters. Non-cool core clusters have a constant temperature profile with a cooling time larger than the cluster age, which are not the focus of this thesis. Cool core clusters are characterized by dense, lower temperature and entropy ($\propto T/\rho^{2/3}$) gas in the core. The high gas density in the cluster core causes a peak in X-ray surface brightness.

Assuming there is no heating, the `ICM` should radiate its thermal energy in the cooling time

$$t_{\text{cool}} = E_{th}/L_X = \frac{p}{(\gamma - 1)n_e n_H \Lambda(T, Z)}, \quad (1.3)$$

where E_{th} is the thermal energy of the gas, p is the gas pressure, and $\gamma \sim 5/3$ is the adiabatic index or ratio of specific heats for a monoatomic ideal gas. The cooling time of

the gas in the core of cool core clusters is less than ~ 1 Gyr, so large amounts of gas in the cluster core should be cooling to lower temperatures.

A cooling flow occurs when the cooling time is shorter than the age of the cluster [33]. As gas radiates its thermal energy, its entropy decreases and thus causes an increase in gas density. The increase in density causes the gas to fall inward towards the cluster core. Since the gas has moved from its initial radius, the thermal pressure at that radius decreases. To maintain hydrostatic equilibrium, this drives an inflow of gas from larger radii. This is the classical picture of a cooling flow [33, 35]. Under this framework, the increase in gas density will increase the X-ray luminosity which will further accelerate the cooling of the gas. The gas cools to below 10^4 K and then accretes onto the central galaxy [78]. From observed X-ray luminosities of the cores of cool core clusters, this predicts cooling rates of 100 to 1000 $M_\odot \text{ yr}^{-1}$.

Multiple sources of observational evidence for cooling should be consistent with the cooling flow model. Spectroscopic X-ray observations should detect strong emission lines below 1 keV from Fe L [14], which have been mostly absent from sensitive observations by XMM-Newton [92, 120]. Observations of the most extreme systems report cooling rates of only $\sim 100 M_\odot \text{ yr}^{-1}$, which is an order of magnitude less than predicted [85]. Optical and UV observations should detect indirect evidence for cooling from high star formation rates [66, 82], however observed star formation rates in BCGs range from a few $M_\odot$ to a few hundred $M_\odot \text{ yr}^{-1}$ in extreme systems [77], which is much lower than expected. Reservoirs of cold ($T \ll 100$ K) molecular gas, predicted to be $10^{11} M_\odot$ or more, from millimeter and sub-millimeter observations of BCGs similarly detect an order of magnitude less gas than predictions, up to $10^{10} M_\odot$ [32, 107]. The products of cooling found in BCGs are only about 5 – 10% of the rates predicted from the classical, unimpeded cooling flow model.

As the classical picture of cooling is not supported by observations, there must exist one or multiple heating mechanisms that offset up to 90% of radiative cooling losses, which can range from 10^{42} to $10^{44} \text{ erg s}^{-1}$. Some of the proposed mechanisms are turbulent heat diffusion [105], thermal conduction [88, 129], heating from mergers [5, 143], cosmic ray heating [12, 54], and feedback from AGN (see reviews [78, 79]). Among these proposed mechanisms, AGN feedback is the most popular. AGN feedback is able to inject sufficient energy into the ICM to offset cooling as well as couple the heating mechanism to the gas reservoir that fuels it, presumably the hot atmosphere of the galaxy cluster.

1.3 AGN Feedback

Almost all massive galaxies have a supermassive black hole at their center [70, 71]. The correlation between supermassive black hole mass and stellar velocity dispersion in the galactic bulge suggests that the black hole and its host galaxy co-evolve. This is known as the M - σ relation [43]. The growth of the central supermassive black hole and its host galaxy are linked. Supermassive black holes that accrete gas and dust from their host galaxy or other surroundings are active galactic nuclei (AGN). The AGN feedback model proposes that the supermassive black holes in the BCGs of galaxy clusters accrete cooling gas and re-eject a fraction of the gravitational potential energy back into the ICM through radiation or some kinetic outflow. AGN feedback therefore couples the cooling rate of the ICM to the accretion rate of the AGN, creating a feedback loop.

Radio AGN were first shown to be interacting with the ICM in the Perseus and Cygnus A clusters through X-ray images by ROSAT [13, 18]. Observational evidence shows that AGN are powerful enough to offset cooling, and that systems with higher ICM X-ray cooling contain more powerful AGN [96]. The cooling time of the ICM around AGN is observed to be 1 Gyr or less, despite the implied high energy output from the AGN [96, 129]. Observations of cavity timescales generally show that the cavities are younger than the surrounding ICM. This implies that AGN are active on similar or shorter timescales to the cooling time [95], which is necessary to prevent run-away cooling.

The energy radiated by the AGN is given by

$$E_{\text{BH}} = \epsilon M_{\text{BH}} c^2, \quad (1.4)$$

where M_{BH} is the mass of the black hole, c is the speed of light, and ϵ is the radiation efficiency or how much of the gravitational potential energy from the infalling mass is radiated by the AGN. Generally, the efficiency is estimated to be $\epsilon \sim 10\%$ [96]. The gravitational binding energy of the galaxy bulge is $\sim M_{\text{bulge}} \sigma^2$, where σ is the velocity dispersion of the stars in the bulge. Taking the ratio of these two quantities, we have

$$\frac{E_{\text{BH}}}{E_{\text{bulge}}} \simeq \frac{\epsilon M_{\text{BH}} c^2}{M_{\text{bulge}} \sigma^2}. \quad (1.5)$$

Taking $M_{\text{BH}}/M_{\text{bulge}} \sim 1.4 \times 10^{-3}$ [55] and that stellar velocity dispersions in the bulge are at most 400 km s^{-1} , we have

$$\frac{E_{\text{BH}}}{E_{\text{bulge}}} \gtrsim 100. \quad (1.6)$$

This implies that the [AGN](#) can have a significant impact on its host galaxy, even if it radiates only a small fraction of the gravitational potential energy. The supermassive black holes have masses of 10^8 to $10^9 M_\odot$, which corresponds to total radiated energies of $\sim 1.8 \times 10^{61}$ to 10^{62} erg. This is sufficient to offset radiative cooling losses of up to $\sim 10^{45}$ erg s^{-1} for 5 Gyr.

The accretion rates of [AGN](#) are measured in terms of their Eddington accretion rate ($\dot{M}_{\text{Edd}}$), which is used to define mass accretion limits. The Eddington accretion rate is achieved when the accretion rate of the supermassive black hole results in an outward radiation force equivalent to the inward gravitational force of the infalling matter. At low accretion rates the matter forms a radiatively inefficient disk, which defines radio mode AGN feedback [[115](#), [116](#), [138](#)]. Otherwise, at higher accretion rates the matter forms a radiatively efficient disk, which defines quasar mode feedback [[69](#)].

1.3.1 Quasar Mode Feedback

Quasar mode [AGN](#) feedback occurs when the supermassive black hole has a high accretion rate ($\simeq 0.01 - 0.25 \dot{M}_{\text{Edd}}$). The high accretion rate is due to large reservoirs of dust and gas in galaxies that feed the [AGN](#). This creates a geometrically thin, optically thick disk that is radiatively efficient [[69](#)]. Supermassive black holes in this state are called quasars. These objects are some of the brightest objects in the universe, boasting luminosities up to 10^{47} erg s^{-1} , and outshine their host galaxies. The bright emission from quasars is mostly due to the accretion disk. Quasars are bright in optical and UV, but also feature X-ray emission due to Compton effects [[113](#)]. The high radiative output from quasars has a significant impact on the surrounding medium.

Quasars drive different kinds of outflows, through thermal pressure and winds, depending on whether radiative losses are significant (momentum-conserving) or negligible (energy-conserving). If the gas is not able to radiate away its energy in the timescale of the outflow, then the outflow is energy-conserving. Otherwise, if the gas is able to cool efficiently, the outflow is momentum-conserving [[42](#)]. Outflows are likely to be some intermediary state between energy-conserving and momentum-conserving.

Thermal pressure from over-pressured hot gas heated by the inner regions of the [AGN](#) pushes the surrounding gas, driving powerful winds. This can create hot nuclear winds of $\gtrsim 10\,000 - 30\,000$ km s^{-1} , which are visible in X-ray, driving outflows of cold gas [[42](#), [125](#)]. Radiation pressure from the [AGN](#) can also drive outflows of gas if the pressure is coupled to the ambient gas and the radiation pressure is greater than the gravitational force. Photons

can transfer momentum to dust grains through scattering or absorption, driving powerful wide-angled outflows on kpc scales of $\gtrsim 1000 \text{ km s}^{-1}$ [104].

Quasar mode AGN feedback is expected to be most active at $z \sim 2 - 3$, where quasar activity is highest as a result of rapid bulge and supermassive black hole growth due to gas accretion from halo mergers at those times [25]. This phase of AGN feedback is powerful enough to quickly eject gas from massive galaxies [44]. Quasar mode AGN feedback is followed by radio mode AGN feedback, which is expected to be responsible for suppressing cooling at later times [78].

1.3.2 Radio Mode Feedback

Radio mode AGN feedback occurs when the supermassive black hole has a low accretion rate ($< 0.01 \dot{M}_{\text{Edd}}$). The accreted gas forms a geometrically thick, optically thin disk that is radiatively inefficient. In radio mode feedback some of the gravitational potential energy of the accreted material is re-ejected back into the surroundings through a pair of polar relativistic jets of energetic particles [8, 9]. These jets are bright in radio emission. Unlike quasar mode feedback which is most effective on kpc scales, jets from radio mode feedback inject energy into the ICM on much larger scales. The jets pour massive amounts of energy into the ICM, creating large X-ray cavities or bubbles, displacing up to $10^{10-12} M_{\odot}$ [11, 78]. The bubbles move buoyantly through the ICM. The combination of jets and bubbles greatly disturb the ICM and heat it through shocks, uplift, turbulence, sound waves, and other mechanisms [21, 78, 79, 96, 141].

The injection of large amounts of energy over large scales from radio mode AGN feedback is expected to be the dominant mechanism that suppresses cooling and star formation in galaxy clusters at late times [15, 25, 61, 86]. However, observations show no signs of overcooling or overheating, so the proposed mechanism must be able to regulate heating and cooling. This mode of feedback self-regulates since the amount of heating is directly tied to the rate of cooling of the surrounding ICM, hence creating a ‘feedback loop’. As described in sections 1.2 and 1.3, cooling gas that accretes onto the black holes is the fuel of the AGN. When the AGN heats the ICM to sufficiently offset cooling, the gas does not cool and fall towards the center of the galaxy cluster, so the AGN effectively starves itself of the fuel used for heating. The connection between the heating rate from the AGN and the cooling rate of the ICM is what makes radio mode feedback self-regulating.

Radio jets are detected in many galaxy clusters, but are especially prevalent in cool core clusters [31, 96]. The dense and X-ray bright atmospheres of cool core clusters provide excellent clarity in probing radio mode feedback, allowing easier detection of the many

features of radio mode feedback (e.g. shocks, cavities). The abundance of observations of cool core clusters from Chandra and XMM-Newton being consistent with radio mode feedback, along with the model’s ability to self-regulate heating and cooling, is why radio mode feedback is considered to be the primary candidate for heating galaxy clusters at late times.

1.4 Jets and Cavities

The accretion of excess cold gas onto the central supermassive black hole results in a pile-up of material around the black hole as an accretion disk. The gas that accretes onto the disk becomes a hot dense plasma. The strong electromagnetic fields from the accretion disk along with the rotation of the black hole results in large, powerful relativistic radio jets that extend deep into the ICM. The simplest case of extracting energy and angular momentum from a Kerr black hole is the Blandford-Znajek process [9]. The rotation from the black hole twists the electromagnetic field lines produced by the accretion disk around the rotation axis of the black hole. Charged particles that are transported along the twisted field lines then extract energy from the black hole and are accelerated to relativistic speeds [9]. The relativistic particles form the jets, emitting radiation through synchrotron emission. However, the mechanisms that create these jets, and furthermore their radio emission, are poorly understood.

The jets emit strongly in the radio band, and have been identified in many systems (see reviews [78, 79]). The jets push the surrounding ICM, heating it through work, and lift the low entropy gas to regions of higher entropy gas. The jets inject kinetic energy into the ICM, creating shock fronts. The jets first move through the ICM supersonically, but then are slowed down by the ICM. The tips of the jets become diffuse and expand to create under-dense elliptical regions of hot gas. These regions are bright in radio emission, and referred to as radio lobes. The radio lobes are correlated with similarly elliptical depressions of roughly 20 – 40% luminosity in X-ray emission relative to the surrounding ICM, called X-ray cavities [78]. These cavities have been identified in up to 70% of cool core clusters [31, 96]. The high detection rate of cavities in cool core clusters implies that radio mode AGN feedback is present in most cool core clusters. This indicates that radio mode AGN feedback and cavities play a vital role in regulating heating and cooling in cool core clusters.

The X-ray images of the Perseus and Hydra A clusters in Figure 1.2 show examples of jets and cavities. The composite image of the Hydra A cluster shows the direct connection between the bright radio jets (in red) and the depressions in X-ray brightness (blue), or

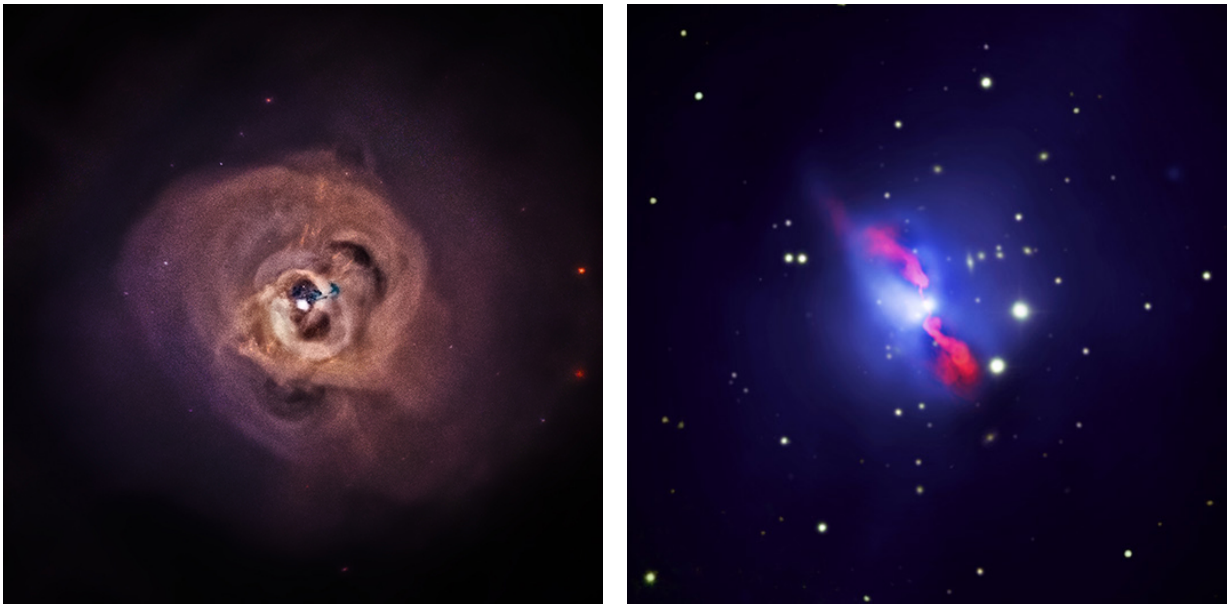


Figure 1.2: *Left*: X-ray image of the Perseus cluster showing multiple cavities and shocks. Credit: NASA/CXC/SAO/[17]. *Right*: Composite image of the Hydra A cluster showing X-rays (blue), radio (red), and optical (yellow). The correlation between jets and cavities are clearly shown. Credit: X-ray: NASA/CXC/U.Waterloo/[67]; Radio: NSF/NRAO/VLA; Optical: Canada-France-Hawaii-Telescope/DSS.

cavities. This shows how the jets carve out the cavities in the ICM. Cavities sizes range from 1 kpc in M87 [46] to 200 kpc in the MS0735.6+7421 [80] and Hydra A [90] clusters.

As cavities are under-dense regions, they rise buoyantly through the ICM via the outward force

$$F_b = gV(\rho_{\text{ICM}} - \rho_{\text{cav}}), \quad (1.7)$$

where V is the volume of the cavity, g is the local gravitational acceleration, and ρ_{ICM} and ρ_{cav} are the densities of the surrounding ICM and cavity [78]. Since the motion of the cavities is due to buoyancy, they rise through the ICM at the terminal velocity, which is determined by balancing buoyancy and drag,

$$v_t \simeq \sqrt{\frac{2gV}{SC}}, \quad (1.8)$$

where S is the cross-section of the cavity, and C is the drag coefficient [21]. The age of the cavity can then be calculated by estimating it as having risen buoyantly at the terminal speed from the cluster center to its current location, as

$$t_{\text{cav}} \simeq \frac{R}{v_t}, \quad (1.9)$$

where R is the distance of the cavity from the center of the cluster [96]. Other cavity age estimates use the sound crossing speed, or the time it takes for gas to replenish the volume displaced by the cavity [78]. However, many unknowns such as viscous and magnetic stresses [27, 98], as well projection effects, can result in underestimating the cavity age and overestimating the cavity power. Estimates of cavity ages range from 10^7 to over 10^8 yr [78]. Some cavity ages indicate that they were formed from older jets from which the cavities have since been decoupled and are still buoyantly rising through the ICM. Indeed, some systems (e.g. the Hydra A cluster) have multiple pairs of cavities, some of which are no longer in contact with the radio jets.

The cavities provide a measure of the mechanical energy expended by the jets to inflate them [81]. The total enthalpy of a cavity is the sum of the work (pV) required to inflate it and the internal energy providing the pressure required to support it, and is given by

$$H = \frac{\gamma}{\gamma - 1} pV = 4pV, \quad (1.10)$$

where p is the gas pressure of the ICM, V is the volume of the cavity, and γ is the ratio of specific heats of the plasma in the cavity ($\gamma = 4/3$ for a relativistic plasma) [79]. If the cavity were filled with non-relativistic plasma, the material would need to have a

temperature of over 20 keV to match the absence of X-ray emission observed in the cavities, so the cavities are likely filled with relativistic plasma from the radio jets [10, 51].

The cavity power can be estimated as

$$P_{\text{cav}} = \frac{H}{t_{\text{cav}}}, \quad (1.11)$$

where t_{cav} is the cavity age. Since the synchrotron radio power of jets and radio lobes only represent a small fraction of the total jet power [112], the cavity power serves as a better gauge of the kinetic power of the radio jet. Radio-based estimates of the jet's mechanical power rely on the ratio of energies between non-emitting particles and synchrotron emitting electrons, k , which is unknown. This ratio has been assumed to be between 0–100 [130]. A low k would provide insufficient mechanical power to offset cooling, however high k is not observationally supported. Despite low radio power, the large cavity sizes from 20 to 200 kpc and the high atmospheric pressures of $\sim 10^{-10}$ dyne cm $^{-2}$ imply mechanical powers from jets orders of magnitude larger than their radio power [6]. Cavity powers range from 10^{41} to 10^{45} erg s $^{-1}$ and tend to match the X-ray cooling luminosities of the clusters they inhabit [34], which is another indication that AGN are able to output sufficient energy into the cluster to offset radiative cooling losses.

A significant issue with cavities is their long term stability, particularly when disconnected from the radio jet. As a cavity rises buoyantly it faces ram pressure from the ICM, which would then cause the cavity to experience Rayleigh–Taylor instability. Additionally, the sides of the cavity will experience Kelvin–Helmholtz instabilities as two gases of different densities, the cavity and the surrounding ICM, are flowing at different speeds [16, 118]. These instabilities should disrupt the cavities over long timescales. The timescales of the evolution of these instabilities are given by

$$\tau_{\text{RT}} \simeq \left(\frac{\lambda_h}{2\pi A|g|} \right)^{0.5}, \quad (1.12)$$

$$\tau_{\text{KH}} \simeq \frac{\lambda_h}{\Delta v} \frac{(\rho_{\text{cav}} - \rho_{\text{ICM}})^2}{\rho_{\text{cav}} \rho_{\text{ICM}}}, \quad (1.13)$$

where λ_h is the size scale of the instability, Δv is the velocity difference between the cavity and the surrounding medium (the ICM), ρ_{cav} and ρ_{ICM} are the densities of the cavity and surrounding medium, g is the gravitational acceleration, and $A = (\rho_{\text{ICM}} - \rho_{\text{cav}})/(\rho_{\text{cav}} + \rho_{\text{ICM}})$ is the Atwood number [28]. Calculations of the Rayleigh–Taylor instability timescales of observed cavities are typically on the order of 1–10 Myr [28], and simulations of cavities indicate that cavities should not be long lived [118]. Therefore cavities should also not

buoyantly rise very far. However, observations show that cavities can survive for long periods of time [37]. It is unclear why observed cavities are so long lived despite such short timescales for these instabilities. Some cavities do in fact show signs of disruption, like in the Perseus, Abell 2052, and M87 clusters [46, 78, 118]. Mechanisms such as magnetic draping [75], internal cavity electromagnetic fields [27, 99], or viscosity [98] have been proposed to help support cavities against disturbances, but overall the stability of cavities is not well understood.

1.5 Heating Mechanisms

Although AGN feedback models are proposed to be the heating mechanisms that offset radiative cooling losses, the actual transfer of energy from the AGN to the ICM is not well understood. Particularly, the heating mechanisms of radio mode feedback are complex and it is unclear how energy is propagated at all scales. Some of the proposed heating mechanisms are outlined below.

1.5.1 Cavity Dissipation

The instabilities described in section 1.4 should cause the cavities to be destroyed and dissipate. After the cavity is destroyed, the mixing of gas of the cavity and the ICM heats the ICM. As mentioned, observed cavities are long lived and do not dissipate on the expected timescales from theoretical predictions and simulations [28, 37, 118]. Since cavities then buoyantly rise to much further distances, cavities can therefore dissipate energy at larger distances.

Additionally, as the cavity rises buoyantly the surrounding gas is displaced and leaves behind empty space. Some of the gas must move to fill that space, effectively converting potential energy from the cavity to kinetic energy (equivalent to the enthalpy lost by the cavity as it rises) in the ICM [7, 78]. The kinetic energy is then dissipated into heat.

1.5.2 Turbulence

As cavities rise buoyantly, some surrounding gas is lifted with the cavity to higher altitudes, which can then detach and fall back to the cluster center. This process generates turbulent motions along the ICM [21], which cascade into smaller and smaller scales to

dissipate the kinetic energy of the gas into heat [141, 142]. Observations find that turbulent heat dissipation may be sufficient to offset cooling, however the uncertainties are broad. The radio jets are also responsible for generating turbulence, as they churn and heat the surrounding gas in the cluster center [79].

In general, turbulence is assumed to be homogeneous, isotropic, and incompressible. Additionally, the turbulent velocity of the gas is assumed to be gaussian random motion. While this may not accurately reflect the conditions of the ICM, some simplifications and assumptions are needed to be able to sufficiently model the dynamics of turbulence [123].

Turbulence generates eddies of varying length scales, l , velocities, $v(l)$, and timescales $\tau(l)$. The larger eddies break up into smaller and smaller eddies until the smallest scales where the energy is then dissipated into heat. The largest scale at which the turbulent motions are driven is defined as the ‘injection scale’. Kolmogorov turbulence predicts that, for a fluid with a sufficiently large Reynold’s number, the velocity field of the eddies is self-similar, and therefore the injected power is constant, over a range of scales [68]. The energy dissipation rate due to turbulence is

$$\dot{E}_{\text{turb}} \sim \rho \frac{v^3}{l} = \rho \frac{v^2}{\tau}, \quad (1.14)$$

where ρ is the density of the fluid.

The injection scale of the turbulent motions and the average velocity dispersion of the gas are enough information to measure the diffusion rate of everything advected by the gas (e.g. metals), along with the energy that is dissipated into heat through the turbulent cascade [145]. Simulations find that turbulent diffusion coefficients of $D_{\text{turb}} \sim 10^{28} - 10^{29} \text{ cm}^2 \text{ s}^{-1}$ match observations [97, 128].

Several methods exist to directly study turbulence in the ICM, such as mapping the line-of-sight velocities to a velocity structure function [140], or indirectly, such as surface brightness fluctuations [139]. Unfortunately, existing X-ray observatories lack sufficient spectral resolution to constrain ICM turbulent velocities. The injection scale is not well understood but can be estimated, such as the bubble size or the scale at which 50% of the light along the line of sight is emitted (e.g [103, 133]). Since the injection scale and the velocity dispersion define the eddy timescale, estimates must be careful to avoid injecting too much energy over a short timescale.

1.5.3 Weak Shocks and Sound Waves

The relativistic jets can create weak shocks in the surrounding gas in the cluster core, which can dissipate heat. Weak shocks create a small increase in the entropy of the gas,

and also operate on shorter timescales than the cooling time of the gas. Although a weak shock individually cannot heat much, the accumulation of many shocks can [45]. Weak shocks are only effective at heating at small radii [79]. The jets also create sound waves that propagate throughout the surrounding gas at the sound speed, which dissipate heat through thermal conduction and viscous dissipation [79]. Sound waves are more effective on larger scales than shocks. Sound waves could be a significant source of heating in the Perseus cluster [36, 38].

1.6 This Thesis

The establishment of the AGN feedback model provides potential solutions to the balancing of heating and cooling in galaxy clusters. This model both heats the surrounding ICM to prevent over-cooling, and self-regulates by driving the outflow of the gas that feeds it through jets and cavities. Observations of cool core clusters with Chandra and XMM-Newton, particularly detections of cavities, shock fronts, and turbulence and measurements of temperature and velocities, provide an abundance of information on how AGN feedback works. However, the precise mechanisms of AGN feedback, particularly the flows of cold and hot gas and how energy is dissipated throughout the ICM, are still unknown. With the launch of XRISM, high resolution spectroscopy can now be applied to these systems to test the finer details of these models.

In this thesis, we used XRISM *Resolve* data to spectroscopically analyze three galaxy clusters. In Chapter 2, I describe the instruments, analysis techniques, and spectroscopic models used. In Chapter 3, we present measurements of the radial profiles of velocity dispersion, redshift, and metal abundance of the Perseus cluster using a single-temperature model. We then present a deeper analysis into the temperature structure of the Perseus cluster with emission line ratios and multi-temperature modeling. In particular, we detect a cooler gas component with unique dynamics compared to the one-temperature or hotter gas component counterpart. In Chapter 4, we present measurements of velocity dispersion, redshift, and metal abundance of the Hydra A cluster over the entire pointing. In Chapter 5, we present measurements of velocity dispersion, redshift, and metal abundance of the Cygnus A cluster over the entire pointing. Additionally, we also present detection of a cooler gas component similar to that of the Perseus cluster. Finally, in Chapter 6 I summarize this thesis and highlight the main conclusions.

Chapter 2

Instruments and Software

2.1 XRISM

The X-Ray Imaging and Spectroscopy Mission (XRISM) is an X-ray observatory launched in September 2023 as part of a collaboration between JAXA and NASA, designed to resume the *Hitomi* mission which was unexpectedly cut short in 2016 [121]. It features an X-ray micro-calorimeter detector, *Resolve*, and an X-ray imager detector, *Xtend*. *Resolve* is a 6×6 pixel array used for non-dispersive high resolution (≤ 7 eV FWHM at 6 keV) spectroscopy over 0.3–12 keV over a 3×3 arcmin² field of view, and *Xtend* provides simultaneous CCD quality imaging spectroscopy over a 38×38 arcmin² field of view [121, 122]. For observations the instrument is calibrated with a radioactive Fe-55 source in the filter wheel. Photons are detected as pulses, or ‘events’, and are graded as a function of the time difference between events. In general only the highest graded events, which have a minimum of ± 70.72 ms between events [122], are used in spectroscopic analysis (e.g. [76, 133]). Unfortunately, the gate valve designed to protect the instruments during launch is not open, causing significant loss of signal at lower energies, and even complete loss below 1.7 keV [76]. This thesis focuses only on work with *Resolve*.

2.2 Chandra

The Chandra X-ray Observatory is an X-ray telescope that was launched on July 23, 1999. It features a CCD imaging spectrometer, *ACIS*, specially designed to take X-ray images of target objects while also measuring the energies of the incoming photons. This allows

Chandra to produce high spatial resolution (0.5 arcsec) images with corresponding spectra over 0.2–10 keV. The abundance of public data from Chandra’s previous observations of many galaxy clusters serves as a reference for scientific interpretation of XRISM results. Images generated from Chandra data are used in XRISM auxiliary response generation as source images for ray-tracing. Fits of Chandra spectra can be used to impose constraints on model fitting of XRISM spectra. The software CIAO 4.17 [48] is used to process Chandra data.

2.3 Redistribution Matrix & Auxiliary Response Files

The [Redistribution Matrix File \(RMF\)](#) is responsible for mapping detector pulses to energy space. The probability of a pulse height measured by the detector is a function of the energy of the incoming photon. These observed energies are spread due to the detector gain and energy resolution, which is expressed as a matrix [48], and can be affected by numerous sources. With XRISM, the [RMFs](#) can account for the gaussian core, exponential tail, instrumental line, escape peaks, and electron loss continuum (Table A.1). The ‘size’ of the [RMF](#) indicates which features are included. Large size [RMFs](#) account for all features except the electron loss continuum, and extra large size [RMFs](#) account for all features.

The [Auxiliary Response File \(ARF\)](#) combines the instrument’s effective area and quantum efficiency into a single curve as a function of energy. The effective area measures the instrument’s ability to collect photons at different energies, which depends on the materials used in the mirrors, reflectivity, mirror geometric area, off-axis vignetting (which depends on the angle of the observation), and quantum efficiency [48]. Many of these factors are strong functions of energy. The quantum efficiency describes the fraction of photons registered by the detector. For example, a quantum efficiency of 80% means that out of 10 photons the detector produces 8 counts. Ideally the quantum efficiency is 100%, but this is never the case. The [ARF](#) can be plotted as a curve of effective area as a function of energy [122].

2.4 Spatial Spectral Mixing

[Spatial-Spectral Mixing \(SSM\)](#) is the use of both spatial and spectral information to provide a better understanding of the model components of a fit, especially when the object has multiple observations over a spatial range. In the context of XRISM, this involves either splitting a single observation into two or more sub-FOV regions (i.e. subsets of

detector pixels), accounting for pixel overlap from different observations, accounting for photon contributions from nearby regions of the sky (which may have observations), or a combination of these, to spatially resolve the spectroscopic data. For each spectrum, an [ARF](#) is generated to account for each nearby region expected to contribute photons, due to the PSF of the instrument, to the spectrum. This allows for each model component to fit both the source spectrum and its contributions to nearby region spectra. This ensures that the models used in simultaneous fitting of multiple sub-FOV regions or observations are more accurate reflections of the spatial regions they are designated to represent. This technique is prevalent in the analysis of the Perseus cluster (Chaper 3), and plays a key role in the data analysis and subsequent interpretation.

2.5 Non-X-Ray Background

In addition to the spectrum measured from the target object, there is also a [Non-X-Ray Background \(NXB\)](#). This includes all the X-ray signal that is not produced by the target or the background noise. The NXB is due to particles hitting the detector, electrical crosstalk, and other high energy events that may affect the detector [122].

For each observation, a [NXB](#) spectrum is extracted with the `rslnxbgen` task, which uses the database of *Resolve* night-Earth data. The spectrum is then modeled empirically [84, 103, 133]. The model consists of a continuum component and 13 gaussians between 1.8–10 keV to represent different detector background emission lines such as Al $K\alpha$, Mn $K\alpha$, and Ni $K\alpha$. This model is either fit on its own and included as a frozen contribution to the observation spectrum, or allowed to vary during the fit. The [NXB](#) is $\lesssim 2 \times 10^{-3}$ counts $\text{s}^{-1} \text{keV}^{-1}$ on average, which is significantly lower than most observed spectra [122]. However it provides significant contributions below 2 keV and above 8 keV for bright objects, or throughout the entire spectrum if the observation is dim or if only a small subset of detector pixels are used. When applied to a subset of pixels the [NXB](#) is scaled accordingly to properly estimate its contribution.

2.6 Xspec

Spectroscopic analyses in this thesis are executed through Xspec [1]. This section covers in detail the major models and analysis features used.

2.6.1 Models

The main model components used in all fits and spectra are: **TBabs**, **bapec**, and **powerlaw**. **TBabs** is a multiplicative model component, representing the Tuebingen-Boulder ISM absorption model [131]. The main parameter of this model is N_{H^2} , which represents the hydrogen column density along the line of sight in cm^{-2} . For each object this value can be extracted from the HEASARC nH tool, which references the 2016 full-sky H I survey [57].

The **bapec** model is responsible for the emission spectrum of a diffuse gas in CIE with some metallicity and velocity dispersion. Xspec calculates this model using atomic continuum and emission line data from the AtomDB atomic database [47]. In all analysis the database used is version 3.0.9. This model component is responsible for measuring the redshift, velocity broadening of emission lines, and mean abundance of metals. The variants **bvapec** & **bvvapec** are used to model the abundances of individual elements – notably Si, S, Ar, Ca, Fe, and Ni – separately rather than an averaged abundance. These abundances are calculated in reference to an abundance table. The table used in all analysis in this thesis is the proto-solar abundance table by Lodders et al. (2009) [73].

Non-thermal continuum components of the spectra (e.g. the AGN) are modeled with a power law. The **powerlaw** model is given by

$$A(E) = NE^{-\Gamma}, \quad (2.1)$$

where N is the normalization and Γ is the photon index [1].

In some clusters (e.g. Perseus) the Fe xxv He α w line is suppressed due to resonant scattering, which occurs due to ions absorbing line photons and nearly instantaneously re-emitting them in different directions [23, 50]. This effect is not accounted for in the CIE plasma model. To account for this, the line is either omitted from the fit or removed from the plasma model and modeled with a gaussian. The red-shifted gaussian profile **zgauss** is given by

$$A(E) = \text{Norm} \times \frac{1}{(1+z)\sigma\sqrt{2\pi}(1 - \text{erf}(-E_0/(\sqrt{2}\sigma)))} \exp\left(\frac{-(E_0(1+z) - E)^2}{2\sigma^2}\right), \quad (2.2)$$

where E_0 is the line energy in keV, σ is the line width in keV, and Norm is the total counts $\text{cm}^2 \text{ s}^{-1}$ in the line, all of which are in the source frame [1].

2.6.2 Statistics

Due to observation time constraints, noise, reprocessing, and sometimes intrinsic low target brightness, a significant number of bins in high resolution spectra will have few to no counts.

The chi-squared statistic becomes problematic when fitting these types of spectra. The denominator of the chi-squared statistic is the variance, and since bins with low to no counts cannot accurately estimate the variance (which is achieved by assuming a Poisson distribution), this can create biases in the results [1]. Therefore it is standard to use a different estimator called the Cash statistic, or C-statistic, which avoids this issue [1, 20]. The C-statistic is given by

$$C = -2 \ln \hat{L} = -2 \sum_{i=1}^N (n_i \ln e_i - e_i - \ln n_i!), \quad (2.3)$$

where $\hat{L}$ is the likelihood, e_i is the expected number of counts, n_i is the number of counts in each bin, and N is the total number of bins [20].

Chapter 3

Perseus

Some of the contents and materials used in this chapter are presented in XRISM Collaboration (2025) [133], of which I am a co-author, and J. Meunier et al. in Prep [84], of which I am the main author. Details are declared in the Statement of Contributions.

3.1 Introduction

The Perseus cluster is a cool core cluster. It is the brightest nearby X-ray galaxy cluster, featuring cavities, shocks, ripples, and sloshing gas (Fig. 1.2) [38, 40, 108]. The super-massive black hole in the BCG, NGC 1275, interacts with the ICM by inflating bubbles of relativistic plasma, seen in the form of X-ray cavities. These bubbles rise through the ICM due to buoyancy, displacing the hot gas and causing turbulence [141]. Evidence of ongoing mergers from infalling galaxies is seen, causing sloshing motions of the gas seen in the form of spiral structures in the X-ray residual image (e.g. [22, 114, 144]).

Perseus has previously been observed with Hitomi [58], detecting velocity dispersions of $\lesssim 180 \text{ km s}^{-1}$ in the inner $\sim 60 \text{ kpc}$. These measurements indicate a quiescent core, in contrast to the high jet powers. Further efforts were made to extract multiple temperature structure in the inner regions using emission line ratios and multiple temperature modeling [24]. A combination of 3 keV and 5 keV gas was detected providing potential evidence for multiple temperature structure in the core region of the cluster, but attributed to projection of the radial temperature gradient along the line of sight.

Perseus has been extensively observed with Chandra, which confirmed the cavities and identified shock fronts and sloshing gas in the cluster core [38, 40, 108]. The gas in the

inner ~ 60 kpc has multiple phases, having different distributions of mass at different temperatures (0.5–4 keV) in the plane of the sky, including a sloshing gas spiral structure at 2 keV, demonstrating that the multiple temperature nature of the gas is not just a projection effect [40].

The temperature of the gas can be estimated by the flux ratios of different emission lines. Flux ratios of different transitions in the same ion can be used to estimate the excitation and ionization temperatures of that species in the plasma. Flux ratios of different ionization species represent the ion fraction of each element [24]. These measurements should match the gas temperature derived from the continuum shape if the plasma is a single temperature gas in collisional ionization equilibrium (CIE). A difference between the temperature estimated using flux ratios and the continuum shape may indicate a complex temperature structure or that the plasma is out of collisional ionization equilibrium. Deviations due to multiple temperatures can be modeled. The high spectral resolution of Resolve ($\Delta E \sim 5$ eV at 6.4 keV) allows for the precise measurement of fluxes of the brightest lines and potential multiple temperature structure from features of the emission lines or the continuum shape.

3.2 XRISM Analysis

The XRISM Perseus observation consists of five exposures across four pointings, designated as C0 (ObsIDs: 000154000 & 000155000), C1 (ObsID: 000156000), M1 (ObsID: 000157000), and O1 (ObsID: 000158000). The C0 observations are aimed at the center of the cluster, while the C1–O1 observations span radially outwards in the NW direction (figure 3.1). The two exposure times of the C0 pointing are 48.3 & 50 ksec. The C1 exposure time is 57 ksec, M1 is 92.6 ksec, and O1 is 131.2 ksec. The calibration pixel, 12, is not included in any analysis. Pixel 27 was ignored in all analysis due to gain calibration issues [94]. Only the highest grade primary events were used. The spectral resolution of the Resolve data after reprocessing is $\simeq 4.5$ eV FWHM. All processed data is calibrated with CalDB version 8.

We assume a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We assume the cluster redshift to be $z = 0.017284$ [59], which gives a spatial scale of 21 kpc/arcmin. Reported errors are statistical 1σ errors unless stated otherwise.

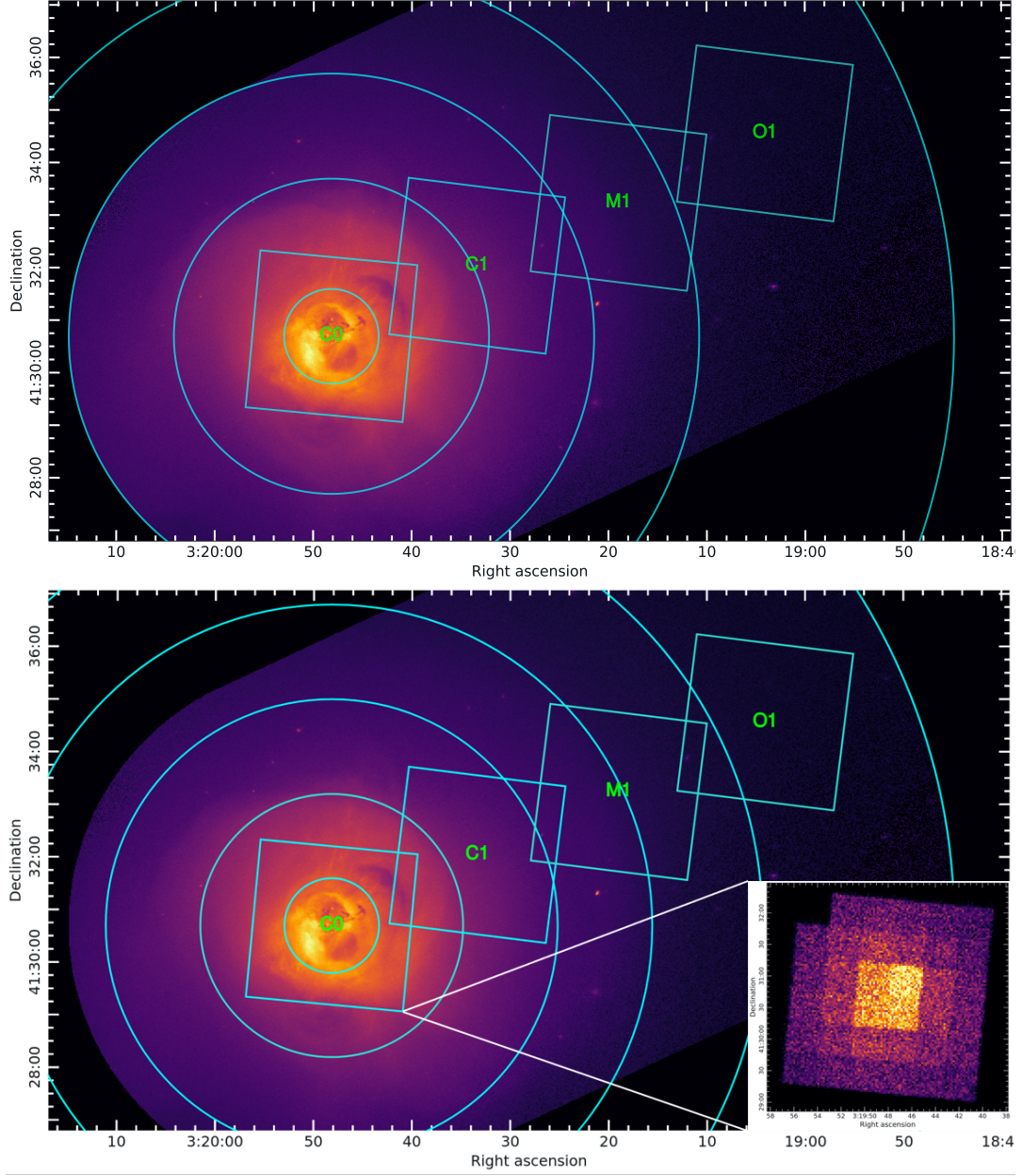


Figure 3.1: The four XRISM pointings (squares) of the Perseus cluster overlaid on the cropped exposure-corrected 2–8 keV Chandra ACIS image [84, 133]. The circles indicate the regions for binning layout 1 (top) and 2 (bottom). The XRISM Resolve view of the C0 pointing is shown. The color map is a square-root scale.

3.2.1 Velocities

The redistribution matrix files (RMFs), auxiliary response files (ARFs), and spectra in this subsection were generated by the Perseus team using the XRISM pre-launch software Build 8. In this analysis large size RMFs were used. The ARF generation is complex, as the pointings overlap and Chandra images were used for more accurate ray-tracing. A master 2–8 keV source image was generated by the Perseus team by combining Chandra *ACIS* images and applying exposure correction (figure 3.1). The AGN in the master source image was masked out and the empty pixels replaced by sampling nearby pixels. The AGN ARFs were generated as a point source located at RA = 3h 19m 48.16s, Dec = 41° 30′ 42.10″, contributing only to the C0 and C1 pointings [133].

The pointings were divided into bin subsections, to get a more detailed radial profile of velocities. Two sets of binning layouts were tested (henceforth binning layouts 1 and 2), one of which (layout 1) is shown in figure 3.1. The binning of the data required splitting observations into sub-FOV regions, which was achieved by separating spectra by pixels according to their respective bin. Since the objective is to model each region separately, spatial-spectral mixing (SSM) is used to account for contributions from nearby regions as well as pixel overlap between observations. As this requires multiple ARFs per bin for each observation, this results in many contributions (up to 33) in a single fit [133].

Each region’s spectra from each pointing were fit in broad band, 1.7–10 keV. The central two regions of both layouts were fit with a four-component *Xspec* model: TBabs*(bapec+po) + NXB, while the remaining bins were fit with a three-component model: TBabs*(bapec) + NXB. The power law is only relevant for the inner three regions as it is treated as a point source, as described in the ARF generation. The Fe xxv He α w line was removed for the central two regions for both bin layouts, to avoid suppression of the bapec models in those bins due to resonant scattering. The hydrogen column density, $N_{\text{H}2} = 1.38 \times 10^{21} \text{ cm}^{-2}$, and power law photon index, $\Gamma = 1.7$, were kept frozen during fitting.

Tables 3.1 and 3.2 show the results for the fits to each region for both binning layouts. The temperatures, metal abundances, velocity dispersions, and bulk velocities are plotted in figures 3.2–3.5. The bulk velocity, v_{bulk} , was obtained by converting redshift to peculiar velocity relative to the redshift of the BCG, $z_{\text{BCG}} = 0.017284 \pm 0.000039$ [59]. A barycentric correction, obtained with the HEASoft task *barycen*, is then applied. The equation for v_{bulk} is:

$$v_{\text{bulk}} = \frac{c(z - z_{\text{BCG}})}{1 + z_{\text{BCG}}}. \quad (3.1)$$

The barycentric corrections are -25 km s^{-1} for pointings C0 & C1 and -26 km s^{-1} for pointings M1 & O1.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Radius (arcmin)	0 – 0.9	0.9 – 3	3 – 5	5 – 7	7 – 11.85
$k_B T$ (keV)	2.82 ± 0.06	$4.00^{+0.04}_{-0.03}$	$5.05^{+0.12}_{-0.11}$	$5.68^{+0.18}_{-0.16}$	$7.16^{+0.29}_{-0.23}$
Z ($Z_\odot$)	0.70 ± 0.03	0.68 ± 0.02	0.44 ± 0.02	0.51 ± 0.03	0.33 ± 0.02
z ($\times 10^{-2}$)	1.795 ± 0.005	1.754 ± 0.002	1.700 ± 0.003	1.701 ± 0.005	1.778 ± 0.008
v_{bulk} (km s $^{-1}$)	175 ± 19	52 ± 13	-110 ± 15	-108 ± 19	123 ± 27
σ_v (km s $^{-1}$)	183^{+24}_{-22}	131^{+8}_{-7}	85^{+14}_{-15}	171^{+17}_{-16}	195^{+25}_{-23}
N _{bapec}	0.074 ± 0.002	0.254 ± 0.003	0.179 ± 0.004	0.036 ± 0.001	0.029 ± 0.001
Γ	1.7		–	–	–
N _{powerlaw}	0.0098 ± 0.0002		–	–	–

Table 3.1: Broad band fit results of the Perseus observations using binning layout 1. The total fit C-stat/dof is: 157867/165654. Errors represent 1- σ statistical uncertainty.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Radius (arcmin)	0 – 0.9	0.9 – 2.5	2.5 – 4.3	4.3 – 6.1	6.1 – 8.2	8.2 – 11.8
$k_B T$ (keV)	3.72 ± 0.07	3.78 ± 0.04	$4.76^{+0.10}_{-0.09}$	5.75 ± 0.21	$6.12^{+0.33}_{-0.30}$	7.39 ± 0.32
Z ($Z_\odot$)	0.60 ± 0.03	0.65 ± 0.02	0.46 ± 0.02	0.56 ± 0.04	$0.41^{+0.05}_{-0.04}$	0.32 ± 0.03
z ($\times 10^{-2}$)	1.772 ± 0.005	1.746 ± 0.004	1.702 ± 0.003	1.672 ± 0.006	1.723 ± 0.008	$1.788^{+0.009}_{-0.010}$
v_{bulk} (km s $^{-1}$)	106 ± 19	28 ± 17	-104 ± 15	-195 ± 21	-42 ± 27	153 ± 32
σ_v (km s $^{-1}$)	168^{+18}_{-17}	144^{+14}_{-12}	77^{+13}_{-14}	170^{+21}_{-20}	129 ± 30	188^{+29}_{-27}
N _{bapec}	0.090 ± 0.002	0.190 ± 0.004	0.200 ± 0.004	0.058 ± 0.002	0.017 ± 0.001	0.019 ± 0.001
Γ	1.7		–	–	–	–
N _{powerlaw}	0.0061 ± 0.0003		–	–	–	–

Table 3.2: Broad band fit results of the Perseus observations using binning layout 2. The total fit C-stat/dof is: 169571/182248. Errors represent 1- σ statistical uncertainty.

A key component to the analysis of the inner regions is the AGN `powerlaw` component. One may naively expect that simply letting both the photon index, Γ , and normalization N_{powerlaw} , be free to vary in the fit to find the best-fit values should be sufficient. Unfortunately, this is not true in practice. Early analysis showed that this basic approach resulted in a large, $\Gamma > 2$, photon index that was slightly degenerate with the `powerlaw` normalization. This resulted in relative fluxes between the CIE components and AGN component to be inconsistent with Chandra observations. This also resulted in inflated abundances in the CIE components. The power law flux and photon index were constrained with measurements from Chandra data. The constraints were obtained by fixing the relative fluxes of the sky regions 1–3 of the second binning layout, as well as measuring the equivalent width of the Fe He α complex with different power law parameter values [133]. The Perseus team found that the best fit photon index is $\Gamma = 1.71^{+0.04}_{-0.05}$ with multiple methods constraining $\Gamma = 1.6$ – 1.8 and the power law flux $\text{Flux}_{2-10\text{ keV}} = 42^{+1}_{-1} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ [133]. The photon index of the power law emission from the AGN is less variable than the flux, therefore we chose to fix $\Gamma = 1.7$ and allow the normalization to vary in the fit.

3.2.2 Emission Line Ratios

The RMFs, ARFs, and spectra in this section were generated with the XRISM pre-launch software Build 8. ‘X’ size RMFs are used, and the source image used for ARF generation is the same master source image described in section 3.2.1. The data was analyzed with Xspec 12.14.1.

We performed fits on 1.8–2.7, 3.0–4.8, and 6.4–8.5 keV bands for the C0 and C1 pointings. Figure 3.6 shows the narrow band fits of the C0 spectrum. We detect Ly α & β , and He α & β lines for Si, S, Ar, Ca, and Fe. Additionally, we detect Ly γ lines for S, and He γ - ϵ lines for Fe.

To measure the observed fluxes of the emission lines, we created an alternate version of the `apec` emission line FITS table in Xspec where the target emission lines were removed. The lines we chose to measure fluxes for are provided in Table 3.3. The Lyman series doublets, with the exception of Fe xxvi Ly α , are unresolved, so the gaussian centroids, widths, and relative normalizations are tied to each other (see columns 4–6 of Table 3.3). Some line fluxes were too low to measure fine structure, so they were modeled with a single gaussian.

We model the narrow bands with `TBabs*(bapec + (N  $\times$  zgauss) + powerlaw) + NXB`, where each narrow band fit has N red-shifted gaussians according to Table 3.3. For the model to be consistent across all fits, we freeze some of the `bapec` parameters ($k_B T$,

abundance, and σ) and `powerlaw` photon index & normalization to results of a single-temperature fit for each pointing, provided in Table 3.5. The redshifts of the gaussians are all tied to the redshift of the `bapec` model. The best-fit gaussian parameters of each emission line for both pointings are provided in Table 3.4. Some lines or doublets that were detectable in C0 had insufficient signal in C1, so they were either omitted or the doublet replaced with a single gaussian. The hydrogen column density, $N_{\text{H}2} = 1.38 \times 10^{21} \text{ cm}^{-2}$, was fixed.

We calculated the emission line ratios for Si, S, Ar, Ca, and Fe for both pointings. We measure the excitation temperature by the flux ratio of different transitions from the same ion, referring to the temperature of free electrons in the plasma, and the ionization temperature by the flux ratio of the different ionization species, referring to the ion fraction of each element [24]. The fluxes of the Ly doublets are summed. The fluxes of lines with unresolved sub-structure are also summed. In the case where a doublet is replaced with a single gaussian in the C1 pointing, that flux is used. These measured ratios are then plotted on the theoretical curves from `AtomDB v3.0.9`, shown in Figures 3.7 & 3.8. The theoretical curves are obtained by plotting the fluxes of the corresponding emission lines as a function of temperature, for every temperature available in the database.

We attempted fits with the `btapec` model and its variants to separately model continuum and emission line temperature according to the results of Figures 3.7 & 3.8 to compare with Hitomi measurements. However, the fits were unable to constrain an emission line temperature in either pointing, while the continuum temperatures were consistent with previous fits. Therefore, the emission line and continuum temperatures are consistent.

3.2.3 Multiple Temperature Models

The `RMFs`, `ARFs`, and spectra in this section were generated with the XRISM pre-launch software Build 8. ‘X’ size `RMFs` are used, and the source image used for `ARF` generation is the same master source image described in section 3.2.1. The data was analyzed with `Xspec 12.14.1`.

To get a more detailed analysis of the multiple temperature structure, we divided the pointings into regions shown in the top of Figure 3.1. We chose these regions to balance maximizing the number of counts and finer spatial binning in the C0 & C1 pointings, since we have seen with emission line ratios that multiple temperatures are difficult to discern. We performed simultaneous fits of all regions, using `SSM` to account for photon contamination, over the 1.8–10 keV band. The best-fit model and its parameters are provided in Table 3.6. The Fe xxv He α w line was removed in regions 1 and 2 and replaced

Emission Line Information		Parameter Links			
Line name	E_0 (eV)	Tied to	E_0	σ	Norm
Si xiii w	1865.0	–	–	–	–
Si xiv Ly α_1	2006.1	–	–	–	–
Si xiv Ly α_2	2004.3	Si xiv Ly α_1	–1.8 eV	$\times 1.0$	$\times 0.5$
Si xiv Ly β_1	2376.6	–	–	–	–
Si xiv Ly β_2	2376.1	Si xiv Ly β_1	–0.5 eV	$\times 1.0$	$\times 0.5$
S xv w	2460.6	–	–	–	–
S xvi Ly α_1	2622.7	–	–	–	–
S xvi Ly α_2	2619.7	S xvi Ly α_1	–3.0 eV	$\times 1.0$	$\times 0.5$
S xvi Ly β_1	3106.7	–	–	–	–
S xvi Ly β_2	3105.8	S xvi Ly β_1	–0.9 eV	$\times 1.0$	$\times 0.5$
S xvi Ly γ_1	3276.3	–	–	–	–
S xvi Ly γ_2	3275.9	S xvi Ly γ_1	–0.4 eV	$\times 1.0$	$\times 0.5$
Ar xvii w	3139.6	–	–	–	–
Ar xviii Ly α_1	3323.0	–	–	–	–
Ar xviii Ly α_2	3318.2	Ar xviii Ly α_1	–4.8 eV	$\times 1.0$	$\times 0.5$
Ar xviii Ly β_1	3935.7	–	–	–	–
Ar xviii Ly β_2	3934.3	Ar xviii Ly β_1	–1.4 eV	$\times 1.0$	$\times 0.5$
Ca xix w	3902.4	–	–	–	–
Ca xix He $\beta_1^\dagger$	4583.5	–	–	–	–
Ca xx Ly α_1	4107.5	–	–	–	–
Ca xx Ly α_2	4100.1	Ca xx Ly α_1	–7.4 eV	$\times 1.0$	$\times 0.5$
Fe xxv z	6636.6	–	–	–	–
Fe xxv w	6700.4	–	–	–	–
Fe xxv He β_1	7881.5	–	–	–	–
Fe xxv He β_2	7872.0	Fe xxv He β_1	–9.5 eV	$\times 1.0$	–
Fe xxv He $\gamma_1^\dagger$	8295.5	–	–	–	–
Fe xxv He $\delta_1^\dagger$	8487.4	–	–	–	–
Fe xxv He $\epsilon_1^\dagger$	8588.5	–	–	–	–
Fe xxvi Ly α_1	6973.1	–	–	–	–
Fe xxvi Ly α_2	6951.9	Fe xxvi Ly α_1	–	$\times 1.0$	–
Fe xxvi Ly β_1	8252.6	–	–	–	–
Fe xxvi Ly β_2	8246.4	Fe xxvi Ly β_1	–6.2 eV	$\times 1.0$	$\times 0.5$
Ni xxvii w	7805.6	–	–	–	–

[†]Fine structure of the line was unresolvable so only one gaussian was used.

Table 3.3: Emission lines used in spectral fits, separated by narrow band. Free parameters are indicated by a hyphen (–).

Line name	C0		C1	
	σ (eV)	Flux ($\times 10^{-5}$ cts/cm ² /s)	σ (eV)	Flux ($\times 10^{-5}$ cts/cm ² /s)
Si XIII w	$0.20^{+1.01}_{-0.20}$	$13.67^{+5.47}_{-4.87}$	—	—
Si XIV Ly α_1	$1.63^{+0.35}_{-0.35}$	$38.49^{+3.57}_{-3.42}$	$3.27^{+1.20}_{-1.06}$	$84.50^{+22.84}_{-20.55}$
Si XIV Ly β_1	$1.23^{+0.72}_{-0.95}$	$5.93^{+1.14}_{-1.05}$	$4.18^{+2.39}_{-1.41}$	$20.27^{+8.97}_{-7.95}$
S XV w	$1.83^{+0.86}_{-0.88}$	$5.30^{+1.37}_{-1.26}$	$2.62^{+3.08}_{-2.62}$	$12.78^{+8.68}_{-7.22}$
S XVI Ly α_1	$1.95^{+0.22}_{-0.23}$	$21.41^{+1.07}_{-1.05}$	$1.08^{+0.62}_{-1.08}$	$43.84^{+5.85}_{-5.48}$
S XVI Ly $\beta_1^{\dagger}$	$1.91^{+0.45}_{-0.43}$	$3.25^{+0.41}_{-0.39}$	$1.15^{+2.67}_{-1.15}$	$7.09^{+3.95}_{-3.03}$
S XVI Ly $\gamma_1^{\dagger}$	$0.20^{+1.16}_{-0.20}$	$0.71^{+0.23}_{-0.22}$	$^{\dagger}1.07$	$1.60^{+2.33}_{-1.60}$
Ar XVII w	$3.11^{+1.87}_{-1.30}$	$3.67^{+0.98}_{-0.81}$	$^{\dagger}6.01$	$8.01^{+3.07}_{-4.58}$
Ar XVIII Ly α_1	$3.51^{+0.61}_{-0.59}$	$5.00^{+0.46}_{-0.45}$	$1.09^{+1.31}_{-1.06}$	$12.55^{+2.50}_{-2.26}$
Ar XVIII Ly β_1	$0.96^{+1.20}_{-0.96}$	$0.50^{+0.18}_{-0.17}$	$2.57^{+2.23}_{-1.40}$	$1.63^{+1.28}_{-1.17}$
Ca XIX w	$3.24^{+0.49}_{-0.46}$	$3.90^{+0.42}_{-0.40}$	$6.48^{+2.34}_{-1.93}$	$13.92^{+3.62}_{-3.36}$
Ca XIX He β_1	$0.68^{+1.35}_{-0.68}$	$0.44^{+0.19}_{-0.17}$	—	—
Ca XX Ly α_1	$3.67^{+0.79}_{-0.71}$	$2.20^{+0.27}_{-0.26}$	$3.98^{+2.22}_{-1.72}$	$9.97^{+2.10}_{-1.89}$
Fe XXV z	$3.71^{+0.18}_{-0.17}$	$10.65^{+0.38}_{-0.37}$	$3.66^{+0.37}_{-0.35}$	$33.81^{+2.43}_{-2.32}$
Fe XXV w	$4.31^{+0.10}_{-0.09}$	$28.19^{+0.55}_{-0.54}$	$3.84^{+0.17}_{-0.17}$	$88.88^{+3.42}_{-3.40}$
Fe XXV He β_1	$4.93^{+0.44}_{-0.41}$	$4.11^{+0.30}_{-0.29}$	$3.86^{+0.76}_{-0.74}$	$14.07^{+1.93}_{-1.79}$
Fe XXV He β_2	$4.93^{+0.44}_{-0.41}$	$0.72^{+0.21}_{-0.22}$	$3.86^{+0.76}_{-0.74}$	$2.47^{+1.27}_{-1.29}$
Fe XXV He γ_1	$5.90^{+1.15}_{-0.99}$	$1.47^{+0.21}_{-0.20}$	$3.14^{+1.17}_{-0.91}$	$4.75^{+1.15}_{-1.04}$
Fe XXV He δ_1	$4.40^{+1.32}_{-1.11}$	$0.70^{+0.16}_{-0.15}$	—	—
Fe XXV He ϵ_1	$9.69^{+6.39}_{-3.93}$	$0.37^{+0.21}_{-0.18}$	$11.70^{+4.92}_{-3.67}$	$3.02^{+1.41}_{-1.28}$
Fe XXVI Ly α_1	$4.16^{+0.32}_{-0.31}$	$3.17^{+0.23}_{-0.22}$	$2.47^{+0.36}_{-0.34}$	$13.68^{+1.52}_{-1.45}$
Fe XXVI Ly α_2	$4.16^{+0.32}_{-0.31}$	$1.73^{+0.18}_{-0.18}$	$2.47^{+0.36}_{-0.34}$	$8.68^{+1.28}_{-1.21}$
Fe XXVI Ly β_1	$8.08^{+3.49}_{-3.38}$	$0.50^{+0.15}_{-0.14}$	$4.29^{+4.19}_{-4.29}$	$2.16^{+0.91}_{-0.79}$
Ni XXVII w	$5.51^{+1.20}_{-0.97}$	$1.29^{+0.21}_{-0.19}$	$7.03^{+12.21}_{-2.83}$	$2.78^{+2.04}_{-1.18}$

† Value is an upper bound.

‡ Doublet replaced by single gaussian in C1 due to insufficient signal.

Table 3.4: Fit results of emission line fluxes and line widths with a fixed **bapec** model described in 3.2.3. Emission lines that are completely tied to other lines are not included. Some lines were not detectable in C1 so they were either omitted or the doublet modeled as a single gaussian.

Table 3.5: Single-temperature baseline models for the line ratio narrow band fits for the C0 and C1 pointings.

Parameter	C0	C1
$k_B T$ (keV)	3.67 ± 0.03	4.44 ± 0.08
Abundance	0.63 ± 0.01	0.54 ± 0.02
z ($\times 10^{-2}$)	1.767 ± 0.001	1.721 ± 0.002
σ (km s $^{-1}$)	173 ± 3	136 ± 6

with a redshifted gaussian. Only a single gaussian is included in each region, with the rest frame energy ($E_0 = 6.7004$ keV) fixed. In the case of a one temperature model in the respective region, the redshift is tied to the **bapec** model. However, in the case of a two temperature model in the respective region the redshift is not tied to allow for variation due to two temperatures. A power law component is included in regions 1–3 to account for the AGN. The power law flux over 2–10 keV was fixed in accordance with best-fit values found in the velocity analysis, $\text{Flux}_{2-10\text{keV}} = 31 \times 10^{-12}$ erg cm $^{-2}$ s [133]. The hydrogen column density, $N_{\text{H}^2} = 1.38 \times 10^{21}$ cm $^{-2}$, was fixed.

For all regions we tested one- (**bvvapec**), two- (**bvvapec+bvvapec**), and temperature distribution (**bvvgadem**) models. The temperature distribution model assumes a gaussian distribution of temperatures with a sigma width. We found that regions 3–5 could not constrain a second temperature component. A temperature distribution model did not significantly improve the statistics of the fit. Combinations of one-, two-, and temperature distribution models were tested for regions 1 and 2. When using a one-temperature for one region and two-temperature for the other in either combination provided significant statistical improvement to the fit over both being one-temperature. In both cases a cooler component with high (≥ 290 km s $^{-1}$) velocity dispersion was indicated. The use of temperature distribution in either or both regions provided no significant improvement or worsened the statistics of the fit.

In order to statistically evaluate which one- or two-temperature model was best for regions 1 and 2, we employed the Bayesian Information Criterion (BIC). The BIC is defined as

$$\text{BIC} = k \ln n - 2 \ln \hat{L}, \quad (3.2)$$

where k is the number of parameters in the model, n is the number of data points, and $\hat{L}$ is the likelihood. The C-statistic is equivalent to the second term (eq. 2.3) [20]. Therefore,

$$\text{BIC} = k \ln n + \text{C-stat.} \quad (3.3)$$

The comparison between the BICs of each best fit model can indicate the significance of introducing new parameters by penalizing overfitting. In general a $\Delta\text{BIC} \geq 10$ suggests strong evidence that the model with the lower BIC is better. We compared full SSM fits with both combinations of one one-temperature model and one two-temperature model in regions 1 and 2. The two-temperature model has 5 more free parameters than one-temperature. Having a two-temperature model in either region was statistically preferred over both regions being one-temperature, with $\Delta\text{BIC} = 10$ for two temperatures in region 1, and $\Delta\text{BIC} = 76$ for two temperatures in region 2. The statistics clearly strongly preferred two temperatures in region 2 over two temperatures in region 1. The best fit for the model with two temperatures in region 2 is provided in Table 3.6, and the best fit for the model with two temperatures in region 1 is provided in Table 3.7.

We attempted to fit both regions 1 and 2 with two temperatures simultaneously. However, using two-temperature models for both regions caused both second temperature components to be unconstrained. This was due to the second component in region 1 fitting residuals in the lower energies ($\sim 1.8 - 2.5$ keV), as this component already had preference for very low ($k_B T < 2$ keV) temperature in the case of two temperatures in region 1 (Table 3.7), which propagated issues to the model in region 2. We imposed stricter parameter limits on the models, however this caused most parameters of the second component of both regions to get stuck at the imposed limits. We attempted to tie the redshifts, velocity dispersions, or both between the two components in region 1 to be able to constrain the fit, as well as with the stricter parameter limits. However, none of these additional constraints resulted in a successful model fit. Therefore, we were unable to successfully fit a model with two temperatures in both regions 1 and 2 simultaneously.

3.2.4 Multiple Temperature Systematics

The AGN component

If both the power law normalization and photon index are free during fitting, Xspec is unable to find parameter values consistent with observations without imposing strict constraints. Therefore we chose to keep the power law flux fixed at the best-fit value found from two approaches constraining the flux and photon index independently of the power law with Chandra data (see discussion in section 3.2.1) [133]. This results in a best-fit value for the photon index of $\Gamma = 1.68^{+0.05}_{-0.09}$, which is consistent with the first paper [133]. The best-fit model, with two temperatures in region 2, with the photon index fixed to $\Gamma = 1.7$ instead of the flux is reported in Table 3.8. This fit results in a larger power law flux of $\text{Flux}_{2-10\text{keV}} = 42^{+1}_{-1} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. This causes a temperature drop in region 1

Table 3.6: Best fit parameters of all sub-FOV regions with SSM from 1.8–10 keV, with two temperatures in region 2. Details of each region model are provided in section 3.2.3. Some abundances were not constrainable in the outer regions, so those parameters were frozen at solar values. The power law photon index best-fit value is $\Gamma = 1.68^{+0.05}_{-0.09}$. Fit C-stat/dof = 156587/163923.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Radius (arcmin)	0 – 0.9	0.9 – 3	3 – 5	5 – 7	7 – 11.85
$k_B T$ (keV)	$3.50^{+0.11}_{-0.19}$	$4.85^{+0.10}_{-0.09}$	$5.28^{+0.12}_{-0.12}$	$5.89^{+0.18}_{-0.17}$	$7.42^{+0.25}_{-0.26}$
Si abund.	$1.02^{+0.10}_{-0.17}$	$0.54^{+0.10}_{-0.09}$	$0.62^{+0.32}_{-0.28}$	$0.62^{+0.51}_{-0.43}$	–
S abund.	$0.86^{+0.10}_{-0.13}$	$0.55^{+0.06}_{-0.05}$	$0.54^{+0.16}_{-0.15}$	$0.87^{+0.29}_{-0.26}$	$0.47^{+0.27}_{-0.24}$
Ar abund.	$0.60^{+0.11}_{-0.12}$	$0.60^{+0.08}_{-0.08}$	$0.74^{+0.24}_{-0.22}$	$0.92^{+0.40}_{-0.36}$	$0.39^{+0.43}_{-0.39}$
Ca abund.	$0.57^{+0.10}_{-0.10}$	$0.66^{+0.08}_{-0.07}$	$0.66^{+0.19}_{-0.18}$	–	–
Fe abund.	$0.68^{+0.03}_{-0.03}$	$0.74^{+0.02}_{-0.02}$	$0.48^{+0.02}_{-0.02}$	$0.54^{+0.03}_{-0.03}$	$0.36^{+0.03}_{-0.03}$
Ni abund.	$0.51^{+0.18}_{-0.18}$	$0.85^{+0.12}_{-0.11}$	$0.44^{+0.17}_{-0.16}$	$0.98^{+0.29}_{-0.27}$	$0.29^{+0.24}_{-0.22}$
z ($\times 10^{-2}$)	$1.792^{+0.003}_{-0.003}$	$1.749^{+0.002}_{-0.002}$	$1.700^{+0.003}_{-0.003}$	$1.701^{+0.005}_{-0.005}$	$1.777^{+0.008}_{-0.008}$
σ (km s $^{-1}$)	141^{+13}_{-13}	111^{+12}_{-9}	91^{+13}_{-14}	177^{+18}_{-17}	202^{+25}_{-23}
Norm ($\times 10^{-2}$)	$7.40^{+0.47}_{-0.24}$	$15.39^{+1.52}_{-0.86}$	$17.99^{+0.35}_{-0.35}$	$3.86^{+0.09}_{-0.09}$	$3.84^{+0.07}_{-0.07}$
$k_B T_2$ (keV)	–	$2.30^{+0.10}_{-0.08}$	–	–	–
z_2 ($\times 10^{-2}$)	–	$1.746^{+0.016}_{-0.016}$	–	–	–
σ_2 (km s $^{-1}$)	–	429^{+64}_{-54}	–	–	–
Norm $_2$ ($\times 10^{-2}$)	–	$12.77^{+0.99}_{-0.93}$	–	–	–

Table 3.7: Best fit parameters of all sub-FOV regions with SSM from 1.8–10 keV, with two temperatures in region 1. Details of each region model are provided in section 3.2.3. Some abundances were not constrainable in the outer regions, so those parameters were frozen at solar values. The power law photon index best-fit value is $\Gamma = 1.60^{+0.05}_{-0.05}$. Fit C-stat/dof = 156654/163923.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Radius (arcmin)	0 – 0.9	0.9 – 3	3 – 5	5 – 7	7 – 11.85
$k_B T$ (keV)	$4.97^{+0.31}_{-0.19}$	$3.96^{+0.04}_{-0.04}$	$5.27^{+0.12}_{-0.12}$	$5.89^{+0.18}_{-0.18}$	$7.42^{+0.25}_{-0.26}$
Si abund.	$0.59^{+0.12}_{-0.10}$	$0.72^{+0.13}_{-0.12}$	$0.62^{+0.32}_{-0.28}$	$0.62^{+0.52}_{-0.43}$	–
S abund.	$0.46^{+0.08}_{-0.07}$	$0.79^{+0.07}_{-0.07}$	$0.46^{+0.16}_{-0.15}$	$0.90^{+0.29}_{-0.26}$	$0.46^{+0.27}_{-0.24}$
Ar abund.	$0.48^{+0.10}_{-0.09}$	$0.67^{+0.08}_{-0.08}$	$0.69^{+0.24}_{-0.22}$	$0.94^{+0.40}_{-0.37}$	$0.39^{+0.43}_{-0.39}$
Ca abund.	$0.65^{+0.10}_{-0.10}$	$0.58^{+0.07}_{-0.07}$	$0.65^{+0.19}_{-0.18}$	–	–
Fe abund.	$0.74^{+0.03}_{-0.03}$	$0.69^{+0.02}_{-0.02}$	$0.48^{+0.02}_{-0.02}$	$0.54^{+0.03}_{-0.03}$	$0.36^{+0.03}_{-0.03}$
Ni abund.	$0.59^{+0.21}_{-0.21}$	$0.76^{+0.11}_{-0.10}$	$0.44^{+0.17}_{-0.16}$	$0.98^{+0.29}_{-0.27}$	$0.29^{+0.24}_{-0.22}$
z ($\times 10^{-2}$)	$1.787^{+0.005}_{-0.005}$	$1.749^{+0.002}_{-0.002}$	$1.701^{+0.003}_{-0.003}$	$1.700^{+0.005}_{-0.005}$	$1.777^{+0.008}_{-0.008}$
σ (km s $^{-1}$)	127^{+17}_{-19}	143^{+9}_{-8}	92^{+13}_{-14}	177^{+18}_{-17}	202^{+25}_{-23}
Norm ($\times 10^{-2}$)	$4.37^{+0.50}_{-0.76}$	$25.02^{+0.31}_{-0.30}$	$18.04^{+0.36}_{-0.36}$	$3.86^{+0.09}_{-0.09}$	$3.84^{+0.07}_{-0.07}$
$k_B T_2$ (keV)	$1.87^{+0.20}_{-0.13}$	–	–	–	–
z_2 ($\times 10^{-2}$)	$1.810^{+0.014}_{-0.014}$	–	–	–	–
σ_2 (km s $^{-1}$)	292^{+62}_{-51}	–	–	–	–
Norm $_2$ ($\times 10^{-2}$)	$4.97^{+0.79}_{-0.68}$	–	–	–	–

Table 3.8: Best fit parameters of all sub-FOV regions with SSM from 1.8–10 keV, with two temperatures in region 2, with power law Γ frozen instead of flux. Details of each region model are provided in sections 3.2.3 and 3.2.4. Some abundances were not constrainable in the outer regions, so those parameters were frozen at solar values. The power law flux best-fit value is $\text{Flux}_{2-10\text{ keV}} = 42_{-1}^{+1} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. Fit C-stat/dof = 156503/163923.

Parameter	Region 1	Region 2	Region 3	Region 4	Region 5
Radius (arcmin)	0 – 0.9	0.9 – 3	3 – 5	5 – 7	7 – 11.85
$k_B T$ (keV)	$2.93_{-0.09}^{+0.09}$	$4.82_{-0.10}^{+0.10}$	$5.27_{-0.12}^{+0.12}$	$5.89_{-0.17}^{+0.18}$	$7.42_{-0.26}^{+0.26}$
Fe abund.	$0.88_{-0.04}^{+0.05}$	$0.74_{-0.02}^{+0.02}$	$0.48_{-0.02}^{+0.02}$	$0.54_{-0.03}^{+0.03}$	$0.36_{-0.02}^{+0.03}$
z ($\times 10^{-2}$)	$1.792_{-0.003}^{+0.003}$	$1.752_{-0.002}^{+0.002}$	$1.700_{-0.003}^{+0.003}$	$1.701_{-0.005}^{+0.005}$	$1.777_{-0.008}^{+0.008}$
σ (km s $^{-1}$)	134_{-13}^{+13}	111_{-9}^{+8}	90_{-14}^{+13}	177_{-17}^{+18}	202_{-23}^{+25}
Norm ($\times 10^{-2}$)	$6.51_{-0.21}^{+0.20}$	$16.15_{-0.88}^{+0.81}$	$17.87_{-0.35}^{+0.35}$	$3.87_{-0.09}^{+0.09}$	$3.84_{-0.07}^{+0.07}$
$k_B T_2$ (keV)	–	$2.30_{-0.08}^{+0.11}$	–	–	–
z_2 ($\times 10^{-2}$)	–	$1.732_{-0.020}^{+0.019}$	–	–	–
σ_2 (km s $^{-1}$)	–	464_{-65}^{+75}	–	–	–
Norm $_2$ ($\times 10^{-2}$)	–	$12.38_{-1.09}^{+1.04}$	–	–	–

along with an increase in Fe abundance. The cooler component temperature, abundances, and velocity dispersion are unaffected, and any significant changes in parameter values in region 2 are 1σ consistent with Table 3.6. The same exercise with the ΔBIC was performed for variations of one- and two-temperature modeling for regions 1 and 2 with the power law photon index fixed instead of the flux. Similarly, the statistics showed preference for two-temperature in either region and significantly more so in region 2.

Atomic databases and resonant scattering

Models using multiple temperature components will be sensitive to finer details of the spectrum, especially emission lines. Differences in atomic databases can have a significant impact on multiple temperature models, as seen in [24]. We tested the best-fit models using the SPEXACT v3.07 and AtomDB v3.1.3 atomic databases instead of AtomDB v3.0.9. Fits using these atomic databases are consistent with the best-fit models reported in Tables 3.6 & 3.7.

The Fe xxv He α w line is suppressed due to resonant scattering in the cluster core

[60], which impacts spectral fitting using standard CIE models. We have addressed this by removing the line from the plasma model in regions 1 and 2, which are affected by resonant scattering, and substituting it with a gaussian. A gaussian may not necessarily be the best option to fit this line, which could influence the multiple temperature result since it is the brightest line in the spectra. We tested the best-fit models using a Voigt profile, as well as omitting the line from the spectra entirely. In both cases the fits are consistent with Tables 3.6 & 3.7.

Spatial-spectral mixing and radial binning

The use of spatial-spectral mixing allows for contributions to the spectral model in a specific region from different regions in the sky. This helps disentangle models when using multiple regions or observations that are in close proximity, or are sufficiently bright to scatter photons over a large area, in order to get more accurate estimates of the gas properties of those specific regions. However, spectral fitting may not necessarily accurately capture the relative fluxes of these regions in favor of a statistical local minimum, especially when using more complex models with multiple flux contributions in the same model (e.g. multiple temperatures, AGN component), as it is challenging to constrain multiple flux contributions from a single region along with contributions from other regions simultaneously.

We applied the same approach as in the first paper to constrain the relative fluxes of regions 1 and 2 for the multiple temperature fit to verify the consistency of the best-fit model [133]. We reprocessed Chandra observations of Perseus (ObsIDs: 3209, 4952, 11714) with CIAO 4.17 [48]. We extracted spectra of regions 1 and 2 from each observation with `specextract`, removing a ~ 9 arcsec diameter circle from the center of region 1 to remove contributions from the AGN point source. We fit each region over 4–7.3 keV with a `TBabs*vapec` model with $N_H = 1.38 \times 10^{21} \text{ cm}^{-2}$ fixed and all abundances tied to Fe. We then measured the flux over 4–6 keV, which is dominated by continuum emission, for each region. We then constrained the multiple temperature XRISM fit by fixing the relative fluxes between regions 1 and 2. The fits using this constraint are consistent with Tables 3.6 & 3.7.

The sub-FOV regions are binned radially outward from the center of the cluster. These regions are different than the main profile reported in the first paper [133]. The immediate effect of this is seen in the velocity dispersion profile in Fig. 3.10, where the velocity jump at ~ 7 arcmin is not detected. Despite this difference, the trends of the temperature and redshift are unaffected, and the differences in velocity dispersion between the data points of the relative outer regions are minimal, as seen in the velocity analysis [133]. Additionally, the cooler component is detected only in the inner two regions, where contributions from

regions 1–3 are far more significant than scattered photons from regions 4 & 5. The outer regions are included in SSM to more accurately fit region 3, which is less affected by contributions from regions 4 and 5 than regions 1 and 2. While this introduces additional minor uncertainty, the focus of this work is on the multiple temperature structure of the inner regions, which is largely unaffected by this difference.

Spatial extent of the cooler component

The cooler component is detected in both the central ~ 20 kpc region and the $\sim 20 - 60$ kpc annulus region. We would expect the cooler component to be significantly detectable in both regions simultaneously. However, the cooler component is only detected when the other respective region is modeled with a single temperature, and the detection is far more significant in the annulus than in the center. This may indicate that the cooler component could be an artifact of spectral modeling or the analysis techniques used. If the cooler component is not an artifact of spectral modeling or SSM, it should still be detected if the core is modeled as a broader region.

We performed the multiple temperature analysis where regions 1 and 2 were combined into a single region, with regions 3–5 included with SSM. The fit results are provided in Table 3.9. We modeled the combined region with two temperatures, and all other regions with one temperature. The power law flux is frozen as before with the photon index left free to vary, and the NXB is included. We find $\Delta\text{BIC} = 23$ statistical significance for two temperatures over single temperature in the combined region. We detect a second component which features a large ($> 300 \text{ km s}^{-1}$) velocity dispersion and cooler ($2.43^{+0.14}_{-0.15} \text{ keV}$) temperature, consistent with Tables 3.6 & 3.7. The hotter component of the model tends to fit the mean of the temperature, redshift, and velocity dispersion profiles across regions 1 and 2. Close inspection of the emission lines verified that the multiple temperature model, in addition to small adjustments for temperature and redshift variation between regions 1 and 2, required a broad cooler component to properly fit broad features of prominent emission lines. This indicates that the cooler component is not an artifact of the spectral analysis.

Energy scale uncertainty below 5.4 keV

Due to XRISM/Resolve’s closed gate valve, the energy scale below 5.4 keV (the lowest energy accessible on-board calibration source) has additional uncertainty. The instrument team guidance is to assume an energy scale uncertainty of $\pm 1 \text{ eV}$ below 5.4 keV. This is

Table 3.9: Best fit parameters of all sub-FOV regions, with regions 1 and 2 combined into a single region and modeled with two temperatures, with SSM from 1.8–10 keV. Details of each region model are provided in sections 3.2.3 and 3.2.4. Some abundances were not constrainable in the outer regions, so those parameters were frozen at solar values. The power law photon index best-fit value is $\Gamma = 1.83^{+0.07}_{-0.06}$. Fit C-stat/dof = 121380/131139.

Parameter	Combined Region 1 & 2	Region 3	Region 4	Region 5
Radius (arcmin)	0 – 3	3 – 5	5 – 7	7 – 11.85
$k_B T$ (keV)	$4.43^{+0.10}_{-0.09}$	$5.29^{+0.12}_{-0.12}$	$5.88^{+0.18}_{-0.18}$	$7.42^{+0.25}_{-0.26}$
Si abund.	$0.74^{+0.07}_{-0.06}$	$0.57^{+0.31}_{-0.27}$	$0.62^{+0.51}_{-0.42}$	–
S abund.	$0.70^{+0.04}_{-0.04}$	$0.49^{+0.16}_{-0.14}$	$0.89^{+0.29}_{-0.26}$	$0.46^{+0.27}_{-0.24}$
Ar abund.	$0.63^{+0.05}_{-0.05}$	$0.73^{+0.24}_{-0.22}$	$0.93^{+0.40}_{-0.37}$	$0.39^{+0.43}_{-0.39}$
Ca abund.	$0.65^{+0.04}_{-0.04}$	$0.66^{+0.19}_{-0.18}$	–	–
Fe abund.	$0.71^{+0.01}_{-0.01}$	$0.50^{+0.02}_{-0.02}$	$0.53^{+0.03}_{-0.03}$	$0.36^{+0.03}_{-0.03}$
Ni abund.	$0.71^{+0.06}_{-0.06}$	$0.46^{+0.17}_{-0.16}$	$0.98^{+0.29}_{-0.27}$	$0.29^{+0.24}_{-0.22}$
z ($\times 10^{-2}$)	$1.761^{+0.002}_{-0.002}$	$1.700^{+0.003}_{-0.003}$	$1.700^{+0.005}_{-0.006}$	$1.777^{+0.008}_{-0.008}$
σ (km s $^{-1}$)	138^{+8}_{-8}	84^{+13}_{-14}	180^{+18}_{-17}	202^{+25}_{-23}
Norm ($\times 10^{-2}$)	$22.12^{+0.16}_{-0.18}$	$18.20^{+0.35}_{-0.35}$	$3.85^{+0.09}_{-0.09}$	$3.83^{+0.07}_{-0.07}$
$k_B T_2$ (keV)	$2.43^{+0.14}_{-0.15}$	–	–	–
z_2 ($\times 10^{-2}$)	$1.787^{+0.011}_{-0.010}$	–	–	–
σ_2 (km s $^{-1}$)	316^{+45}_{-37}	–	–	–
Norm $_2$ ($\times 10^{-2}$)	$11.65^{+1.89}_{-1.72}$	–	–	–

based on observations of instrumental lines of Si K and Al K. An energy scale offset can result in a shift in redshift or if it is pixel dependent, an increase in velocity dispersion, which can have nonlinear effects on spectral modeling. The multiple temperature model is sensitive to the softer energies since the cooler component is sensitive to the emission lines below ~ 3 keV. If the model fit of a region that is confidently single temperature finds varying redshift or velocity dispersion over different narrow bands, this may indicate an energy scale offset. We performed single temperature narrow band fits of 2–4, 4–6, and 6–7 keV for regions 3, 4, and 5 without SSM. Unfortunately, low photon counts in these regions provide poor constraints on redshift and poor or no constraints on velocity dispersion over narrow bands that do not include the Fe xxv emission lines. The lack of precise constraints

prevents us from measuring or ruling out an energy scale offset.

If we assume an uncertainty of ± 1 eV at 2 keV, this results in a systematic uncertainty of $\sim 150 \text{ km s}^{-1}$, which is added in quadrature to the velocity dispersion. This would affect the measured velocity dispersions by $\sim 30 - 40 \text{ km s}^{-1}$. However, as mentioned the true effects on the multiple temperature modeling may be more complex.

3.3 Discussion

3.3.1 Velocity Structure

The temperature, metal abundance, velocity dispersion, and bulk velocity profiles are presented in Figures 3.2–3.5. We find a radially-increasing temperature profile and a radially-decreasing metal abundance profile, trends consistent with typical cool core clusters. Variations in the core are due to spectral modeling effects of the AGN, seen in the systematics analysis in section 3.2.4. The velocity dispersion and bulk velocity profiles suggest interesting dynamics (Figs. 3.4 & 3.5). The radial velocity dispersion profile shows a clear declining gradient in the inner ~ 60 kpc, which is much different to the velocity dispersions in the outer regions. This gradient in velocity dispersion in the inner ~ 60 kpc (Figs. 3.4 & 3.10) suggests that jets and bubbles may be driving turbulence in the core of the cluster [133]. In the second binning layout there is another jump in velocity dispersion at ~ 7 arcmin, which is believed to be caused by a cold front (see [133] Figs. 1–2). The bulk velocities indicate a large offset in bulk motion between the hot X-ray gas and the BCG.

Assuming a Kolmogorov spectrum, we estimate the heating rate due to turbulence as

$$\dot{E}_{\text{heat}} \sim \frac{\rho v_{\text{turb}}^3}{l}, \quad (3.4)$$

where the gas mass density is $\rho = (n_i + n_e)\mu m_p$, n_i and n_e are the number densities of ions and electrons in the gas, μ is the mean molecular weight, m_p is the proton mass, and l is the injection scale [133]. We use the de-projected electron number density given by [22], and the ion number density is given by $n_i = (\xi - 1)n_e$, where $\xi = 1.912$ for a fully ionized plasma. We assume that the velocity dispersion is the turbulent velocity. We estimate the injection scale to be an effective scale, l_{eff} , for each region based on estimates of effective length [133]. The effective length is the size of the volume along the line of sight in the sky region such that the majority of the flux in the spectrum originates from said volume (see Extended Data Fig. 6 of [133]). For this analysis, l_{eff} is taken to be the size of the volume

of which 50% of the flux of the spectrum originates [133]. The heating rate in each region is then given by [103, 133]

$$\dot{E} \simeq \frac{3}{2} \frac{\rho v_{\text{turb}}^3}{l_{\text{eff}}}. \quad (3.5)$$

We calculate the cooling rate as

$$\dot{E}_{\text{cool}} = \frac{\xi - 1}{(\xi \mu m_p)^2} \rho^2 \Lambda(T, Z), \quad (3.6)$$

where $\Lambda(T, Z)$ is the normalized cooling function, which is a function of gas temperature and metallicity, fixed to $2.5 \times 10^{-23} \text{ erg cm}^3 \text{ s}^{-1}$ [119, 133].

Figure 3.9 shows the cooling rate curve and estimated heating rates in each region for both binning layouts. We find that the heating rates of the inner three regions in both layouts, $\sim 100 \text{ kpc}$, lie systematically below the cooling rate. While this suggests underheating in the cluster core, the injection scales are not known. While they are assumed to be the effective length scales, the injection scale in the core could be the bubble sizes ($\sim 5 - 30 \text{ kpc}$), which would increase the heating rates to balance cooling [133]. However, reasonable assumptions about the injection scales, that avoid dumping very large amounts of energy in a small volume over a short timescale, may indicate that turbulence would struggle to balance cooling in the core (cf., [103]).

3.3.2 Line Ratios and Multiple Temperatures

In the central pointing, the excitation temperature measured from the emission lines of Si, S, Ar, and Ca (Fig. 3.7) show scatter across 0–2 keV which could indicate potential for multiple temperatures. However, this result is uncertain due to the large 1σ errors. The measurements from Fe provide constraints on a hotter component, similar to Hitomi measurements. For the C1 pointing measurements from Fe are consistent with Hitomi and the C0 pointing, although with larger errors, while measurements of Si, S, and Ar are too uncertain to provide constraints. For the ionization temperatures (Fig. 3.8) only Si shows any indication of potential for a cooler component. S, Ar, and Ca are consistent with Hitomi. The C0 flux ratios of Fe are consistent with Hitomi. However, there is some preference for hotter gas in C1. The temperature measurements from Fe for both C0 and C1 are consistent with the temperatures measured in the velocity analysis [133] (Fig. 3.10), with the exception of Hee for C1 which is a largely uncertain measurement.

Both pointings have less net exposure than the Hitomi data. This explains the larger error bars on all flux ratio measurements, and why we were unable to get separate con-

straints on the continuum and emission temperatures with the **btapec** model. Due to the large uncertainties, the flux ratios are consistent with a single temperature CIE gas.

The multiple temperature analysis divides the C0 and C1 pointings into three sub-FOV regions, two of which there is a preference for multiple temperatures. As mentioned in section 3.2.3, both regions 1 and 2 prefer a two-temperature model over one-temperature, but significantly more so in region 2, with two-temperature in region 2 having $\Delta\text{BIC} = 66$ over two-temperature in region 1. The hotter component temperatures are consistent with measurements from the emission line ratios of Fe (Figs. 3.7 & 3.8), while the cooler component temperature is roughly consistent with excitation temperature measurements from Si–Ca and ionization temperature measurements of Si as well. Looking more closely at Si xiv & S xvi Ly α and Fe xxv He α (Figs. 3.11 & 3.12), we see that the cooler component is dominant for the Si and S emission lines, and tends to be responsible for the wider broadening of the wings of most emission lines in the spectrum. The hot component is dominant for the other emission lines and tends to be responsible for the peaks of the lines. The impact of the cooler component is most visible in S xvi Ly α , capturing the broader wings of the line while not overshooting the peak. The two-temperature model prefers a broader width for Si xiv Ly α , although it is unclear whether this is a better fit. The Fe xxv He α z line and wide wing at ~ 6.60 keV are better fit by the two-temperature model, however it is unclear if the broader wing at ~ 6.50 keV is a better fit. Interestingly, the Fe xxv He α y line is not well fit by either model, which is seen in other objects as well (e.g. [134]).

While the two-temperature model components seem to trace the different metals at different temperatures, they also measure significantly different velocity dispersions. Figure 3.10 compares radial profiles of the temperature, velocity dispersion, redshift, and bulk velocity of this work and the velocity analysis [133]. The measured velocity dispersions from region 1 and hotter component of region 2 are systematically lower than the velocity analysis [133], with the cooler component of region 2 measuring a very large 400–500 km/s velocity dispersion. The discrepancy between the one-temperature & hotter component and the velocity analysis [133] in regions 1 and 2 can be explained by how the two components trace different emission line features. A one-temperature model would measure slightly larger broadening to account for the wider wings, while the two-temperature model is able to separate the different velocity dispersions into a narrower peak component and wider wing component.

3.3.3 The Cooler Gas Component

The cooler component's emission measure is non-negligible, and is comparable to the hotter component in region 2. The cooler component is detected in the central ~ 60 kpc regardless of the choice of regions in the spectral analysis, and is robust against other systematic effects (see section 3.2.4). In addition to two temperatures being strongly statistically preferred over a single temperature model up to a significance of $\Delta\text{BIC} = 76$, and the emission line features traced by this component discussed in the previous section, this suggests that this component is likely real. We assume the cooler component is physically real and explore its properties.

For the following calculations, we assume the temperature, velocity dispersion, and bulk velocity of the cooler component are those from the model with two temperatures in region 2 (Table 3.6).

The sound speed is given by

$$c_s = \sqrt{\gamma \frac{k_B T}{\mu m_p}}, \quad (3.7)$$

where $\gamma = 5/3$ is the adiabatic index, T is the temperature, $\mu = 0.61$ is the mean molecular weight, and m_p is the proton mass. The cooler gas component, with $k_B T = 2.30^{+0.10}_{-0.08}$ keV, has a sound speed of $c_s = 776^{+17}_{-13}$ km s $^{-1}$. The measured velocity dispersion, $\sigma = 429^{+64}_{-54}$ km s $^{-1}$, is comparable to the sound speed. We can calculate the 3D Mach number, assuming that the velocity dispersion is purely due to isotropic turbulence, as

$$M_{3\text{D}} = \sqrt{3} \sigma / c_s, \quad (3.8)$$

where σ is the measured velocity dispersion. We calculate $M_{3\text{D}} \simeq 0.96 \pm 0.14$ for the cooler component, which would suggest mildly transonic turbulence. The measured velocity dispersion is likely not purely turbulence since region 2 contains bubbles, sloshing, and other features (e.g. [40]). Despite this, the cooler component 3D Mach number is much higher than the hot component ($M_{3\text{D}} \sim 0.16$). The non-thermal pressure fraction is given by

$$\frac{P_{\text{NT}}}{P_{\text{tot}}} = \frac{M_{3\text{D}}^2}{M_{3\text{D}}^2 + 3/\gamma}. \quad (3.9)$$

For the cooler component, this gives a non-thermal pressure fraction of $\sim 33.8 \pm 6.7\%$. This is significantly larger than what is measured in the hotter component ($\sim 1.6\%$), the velocity analysis [133] ($\sim 0.6 - 5\%$), and in other objects [49, 103, 134, 135, 136].

We calculate the cooling time as

$$t_{\text{cool}} = \frac{3}{2} \frac{N k_B T}{n_i n_e \Lambda(T)}, \quad (3.10)$$

where N is the total number density of all species and $\Lambda(T)$ is the normalized cooling function. We fix $\Lambda(T) = 1.86 \times 10^{-23} \text{ erg cm}^3 \text{ s}^{-1}$ for solar metallicity gas at $k_B T = 2.30 \text{ keV}$ [119]. If we assume that the relative normalizations between the hotter and cooler components represent the relative fractions of the total gas mass, using the n_e profile from [22], then we calculate $t_{\text{cool}} \sim 1.45 \text{ Gyr}$ for the cooler component.

The physical interpretation of the cooler component is unclear. It may be disturbed gas introduced by a previous merger. The 2 keV Chandra mass map of the Perseus cluster by [40] shows a spiral structure around the cluster center expanding as it moves outward. Figure 3.13 shows the map with regions 1 and 2 roughly aligned, showing that this spiral lies entirely within these regions. The temperature of the gas in this mass map is close to that of the cooler component, and much of the gas lies within the region where we detect it with highest significance.

Large velocity dispersions, comparable to that of the cooler component, are found in merger simulations. These mergers show spiral structure similar to what is seen in Perseus [146]. The simulated observed line shapes predict non-gaussianity that may be modeled as superpositions of gaussians, which is how the multiple temperature model fits emission lines (e.g. S xvi Ly α , Fig. 3.11). Although the high velocity dispersions in the simulations are associated with gas roughly 2–3 times hotter than what we detect, the relatively cooler sloshing gas in the simulations has the higher velocity dispersion, similar to our findings.

Alternatively, the AGN has a stronger impact on cooler gas. Since the cooler component is only detected in the inner regions, it may instead represent the cooling flow that is being disturbed by the jets and bubbles. Cool gas has been detected around the rims of the inner bubbles [38, 40], and rising bubbles drag cooler gas from the core [21].

The age of the inner bubbles is estimated to be 10^{7-8} yr [39], and are within regions 1 and 2. If we assume that the velocity dispersion is the 1D velocity of the cooler gas that started moving from the cluster center, then we can calculate the crossing time, $t_{\text{cross}} \simeq r/\sigma$, of the cooler gas through regions 1 and 2. For region 1, which is $\sim 20 \text{ kpc}$ in radius, we calculate $t_{\text{cross}} \sim 4.5 \times 10^7 \text{ yr}$. Region 2 is $\sim 40 \text{ kpc}$ wide in addition to region 1. The crossing time from the cluster center to halfway through region 2 is $t_{\text{cross}} \sim 9.1 \times 10^7 \text{ yr}$, and all the way through region 2 is $t_{\text{cross}} \sim 1.4 \times 10^8 \text{ yr}$. Under these assumptions it is plausible for the cooler gas to be detected in regions 1 and 2 as it is consistent with the age of the inner bubbles. The energy to create the cavities is estimated to be $P\Delta V \simeq 8 \times 10^{58}$

erg [39]. Assuming that the cooler gas is a spherical volume of radius R , with the velocity dispersion representing the 1D velocity of the gas, then we estimate the kinetic energy as $\text{K.E.} = \frac{3}{2}m\sigma^2$, where $m = 4\pi \int_0^R \rho(r)r^2 dr$. Deriving the cooler component gas mass from the emission measure of the fit [63]

$$n_e = D_A(1+z)10^7 \sqrt{\frac{\text{Norm} \times 4\pi 1.2}{V}}, \quad (3.11)$$

or from the n_e profile reported by [22], we calculate the kinetic energy to be $\simeq 4.3\text{--}9.8 \times 10^{58}$ erg for a sphere of 20 kpc radius and $\simeq 3.5\text{--}6.7 \times 10^{59}$ erg for a sphere of 40 kpc radius. The assumption that the kinetic energy scales with a factor of 3/2 may not be accurate as the velocity is likely not gaussian random motion, so these calculations are uncertain up to a factor of ~ 2 . Within the broad uncertainties, the energies of the bubbles and the cooler gas component are comparable. Considering the ages, spatial extent, and energies of the bubbles and the cooler gas, it is plausible that the cooler component is cooling gas that has been disturbed by the jets and bubbles.

The spatial extent of the cooler component is unclear. The previous work by [24] suggests that two-temperature structure may be present within region 1. However, both components had temperatures of $k_B T \geq 3$ keV and were attributed to a projection effect of gas along the line of sight rather than two gas components in the core. However, cold gas (0.5–2 keV) is detected by Chandra in the innermost regions ([40], Figure 3.13). Despite detecting the cooler component when combining regions 1 and 2 (see section 3.2.4), the main concern is why the cooler gas is not as significantly detected in region 1 as in region 2. It is possible that the AGN point source is too bright, so there are not enough counts for sufficient statistics for two-temperature models to be as significant in region 1 or well constrained in both regions simultaneously. Additionally, the cooler component we detect at 2.3 keV may not necessarily be the 2 keV gas in Figure 3.13, and therefore may not be similarly spatially distributed. If we assume that the cooler gas is dragged by the bubbles and potentially influenced by the merger dynamics, then it is possible that there is less of this gas component in the core than in region 2. Note that this does not mean that there is less or no cooler gas in the core, it may simply indicate that we cannot extract such precise information with this data.

3.3.4 Abundances

The multiple temperature spectral fitting also reports abundances for Si, S, Ar, Ca, Fe, and Ni (rows 3–8 of Table 3.6). Assuming that the abundances of each element in each region

are mostly independent from each other, and that the errors are gaussian, we can calculate the weighted mean and uncertainty of the ratio of each element with respect to Fe. Since Si and Ca were not constrainable in some regions, those regions are not included for the ratio calculations of those elements respectively. The mean abundance ratios with respect to Fe are provided in Table 3.10. These ratios are consistent with the Solar System and other clusters. Additionally, the abundance ratios are consistent with the more thorough abundance analysis in an upcoming paper. Although tying the abundances of the cooler and hotter components in region 2 together was necessary for successful spectral fitting, it is unknown whether the two gas components should have similar chemical composition.

Table 3.10: Mean abundance ratios with respect to Fe.

Si/Fe	S/Fe	Ar/Fe	Ca/Fe	Ni/Fe
$1.06^{+0.10}_{-0.10}$	$0.89^{+0.07}_{-0.07}$	$0.87^{+0.09}_{-0.09}$	$0.90^{+0.09}_{-0.09}$	$1.06^{+0.12}_{-0.12}$

3.4 Conclusion

We present an analysis of the five XRISM Resolve observations of the Perseus cluster. We performed spectral fitting with single temperature models to derive radial profiles of temperature, metal abundances, velocity dispersion, and bulk velocity up to ~ 250 kpc from the cluster center.

We measure a radially-increasing temperature profile, along with a radially-declining mean abundance profile, which is consistent with typical cool core clusters. We find a radially-declining velocity dispersion profile in the inner ~ 100 kpc, which indicates that jets and bubbles may be driving turbulence in the core (~ 60 kpc) of the cluster. The outer regions have higher velocity dispersions, with a jump at ~ 7 arcmin which may be due to a cold front. We find that the heating rates of the inner ~ 100 kpc lie systematically below the cooling rate. While this may suggest that the core is being under-heated, the uncertainties of the analysis and the unknown injection scale indicate that heating could balance cooling in the core. However, other analyses of the injection scale may indicate that turbulence would struggle to balance cooling in the cluster core.

Additionally, we present a follow-up analysis where we measured emission line flux ratios and performed spectral fitting with multiple temperature models in order to determine the temperature structure of the Perseus cluster. The flux ratios may indicate the existence of a lower temperature component in the central pointing, but due to the large errors all

measurements are consistent with a single-temperature CIE gas. However, the multiple temperature spectral fitting detected a significant cooler gas component in the inner ~ 60 kpc.

The cooler gas component features a high velocity dispersion, potentially mildly transonic turbulence, and a high non-thermal pressure fraction. The dynamics of the cooler gas component are significantly different compared to the one-temperature and hotter component counterparts. It may be explained as sloshing gas from a previous merger, or that the AGN has a stronger effect on colder gas. Comparing the spatial extent and velocity dispersion of the cooler component to the age and energy of the inner bubbles indicates, within the broad uncertainties of the analysis, that the cooler gas being impacted by the AGN more than the hot gas is consistent with observations. However, the complex dynamics and structure of both proposed possibilities make it challenging to fully explain the cooler component, and it may be best explained as a combination of both AGN and merger effects or perhaps a different scenario entirely.

The biggest concern is the lack of detection of the cooler gas component in the inner ~ 20 kpc as significant as in the surrounding $\sim 20 - 60$ kpc. While the proposed scenarios suggest that there would be less of this gas component in the core, it is also possible that there is not enough photons to detect it. Additionally, it may simply be that we cannot extract information with the necessary precision for such analysis with this data. The existence of a cooler broad component is robust to systematic effects, and is therefore likely real. However, the precise temperature, velocity dispersion, bulk velocity, and spatial extent of this component are not clear, as seen from the significant variation from systematic effects.

Deeper observations of this region, particularly focusing on the softer energies, will be necessary to get a better understanding of the cooler component. Detections of this kind in other objects would help shed more light on the dynamics of colder gas in galaxy clusters. However, the lack of such detections in most objects highlights the challenging nature of such analysis.

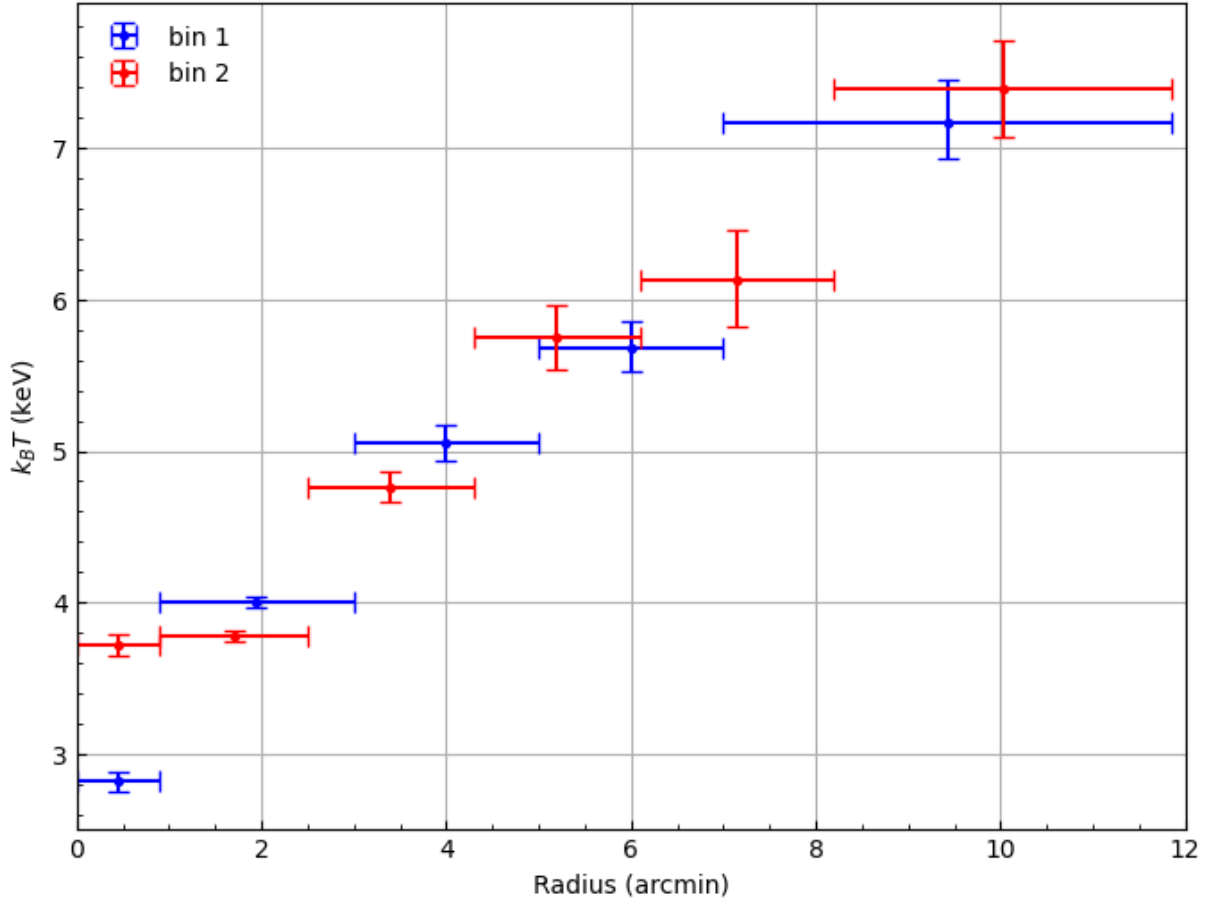


Figure 3.2: Radial temperature profile of the best fit one temperature models of all regions, for both bin layouts.

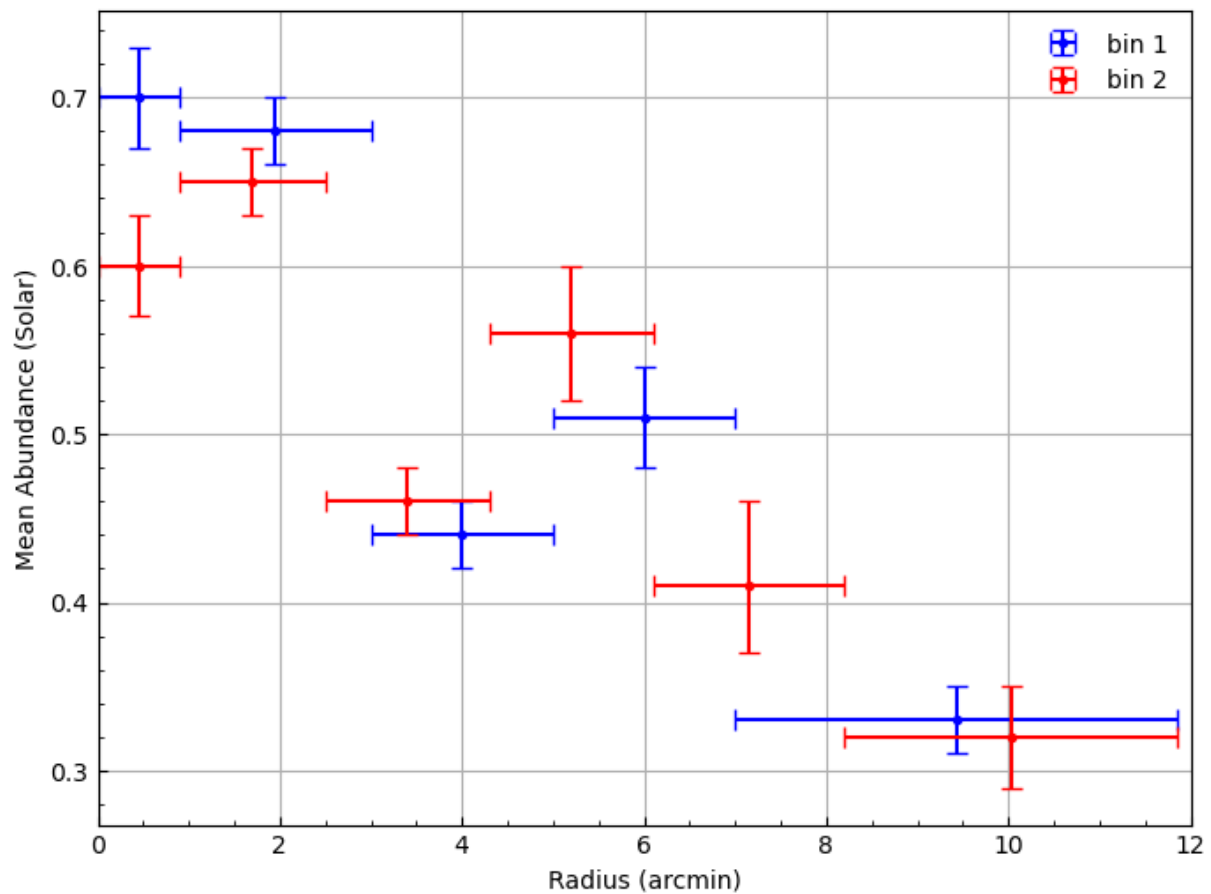


Figure 3.3: Radial mean abundance profile of the best fit one temperature models of all regions, for both bin layouts.

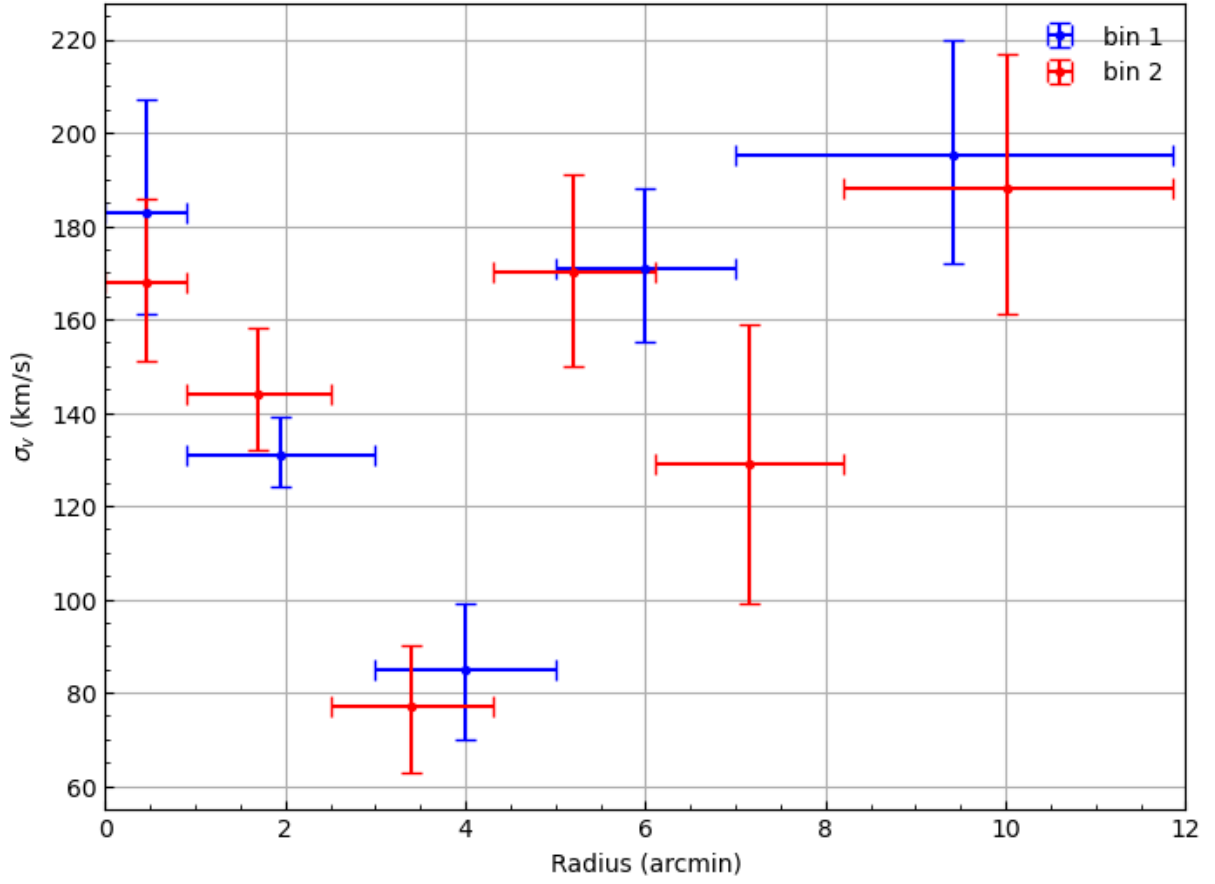


Figure 3.4: Radial velocity dispersion profile of the best fit one temperature models of all regions, for both bin layouts.

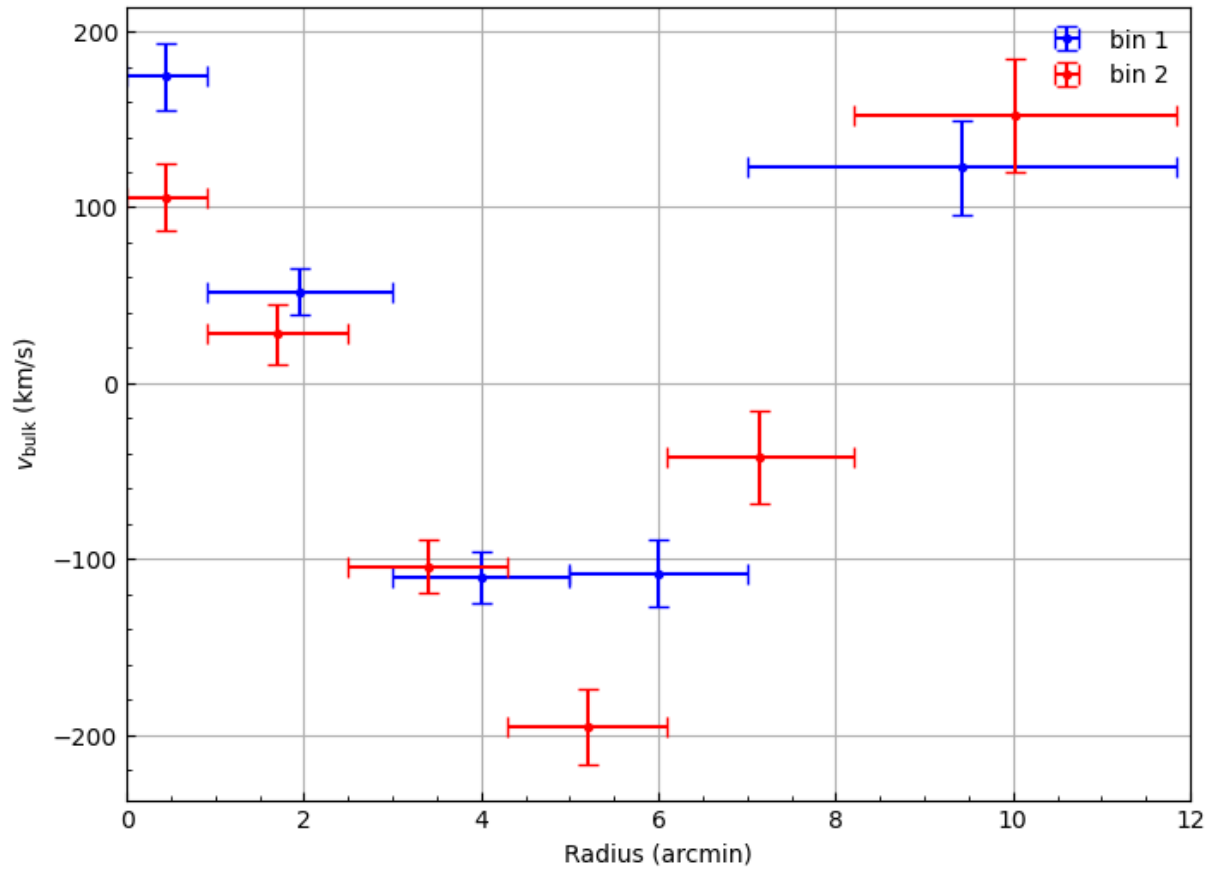


Figure 3.5: Radial bulk velocity profile of the best fit one temperature models of all regions, for both bin layouts.

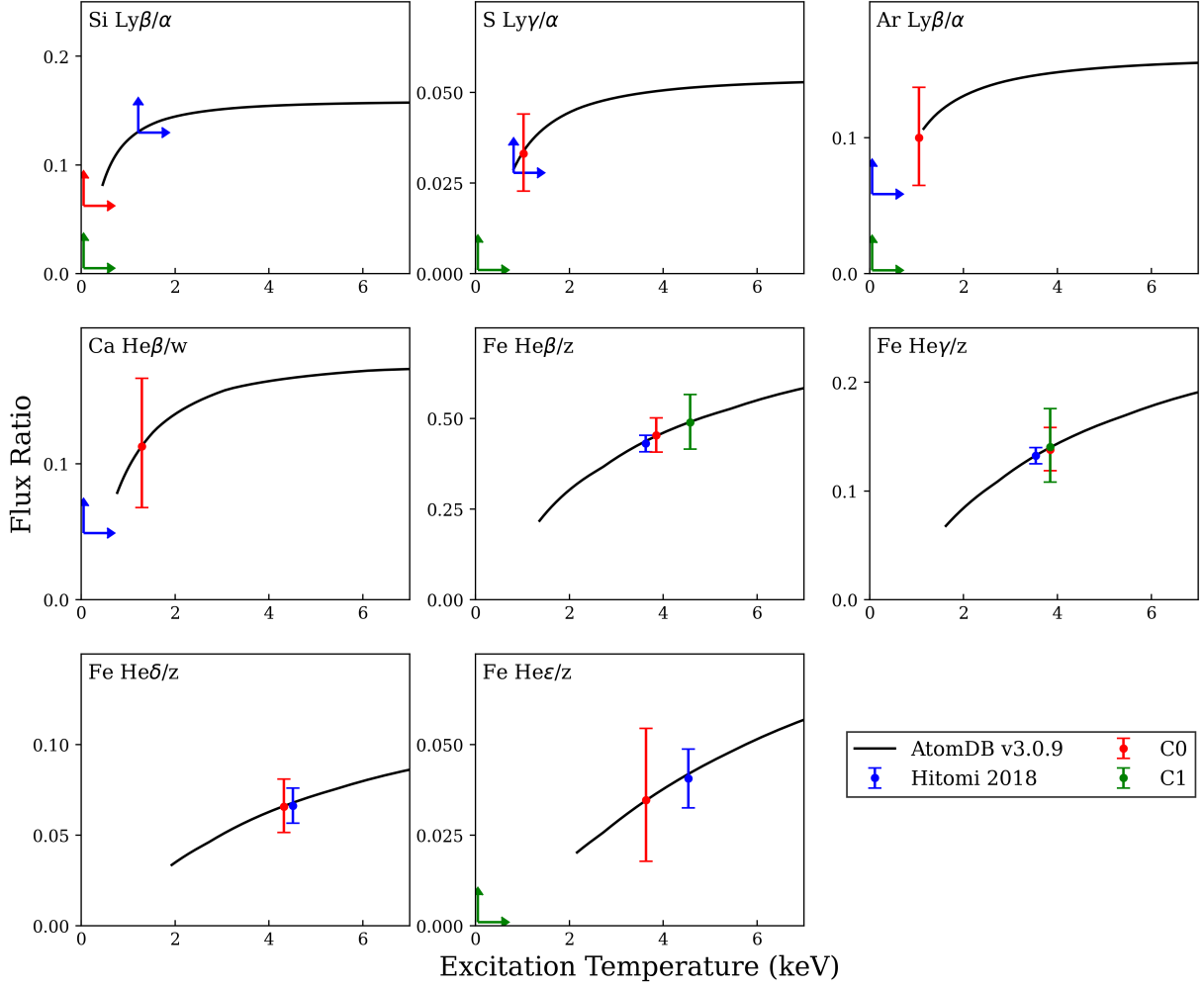


Figure 3.7: The calculated excitation temperatures from the measured flux ratios of different transitions of the same ion, measured for Si, S, Ar, Ca, and Fe, with respect to theoretical curves from **AtomDB** v3.0.9. The theoretical curves are obtained by calculating the flux ratios at each temperature recorded in the atomic database. The measured flux ratios are then plotted on the theoretical curves to infer the temperature. Error bars represent 1σ statistical uncertainties. In the case that the measurement is beyond the scope of the theoretical curve, or if the error is too large and would imply a very large range of temperatures, the data points are instead plotted with arrows to represent 3σ lower limits.

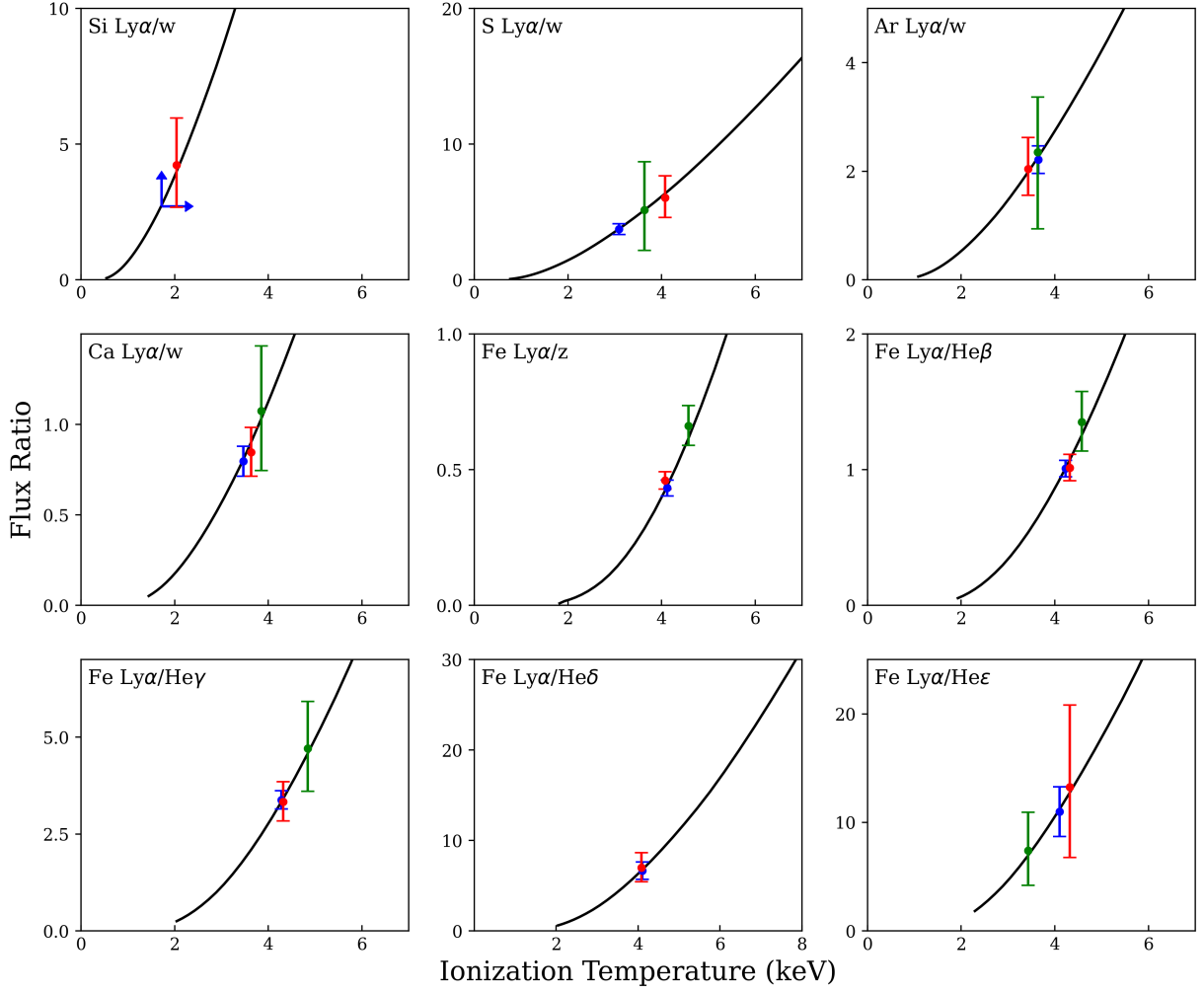


Figure 3.8: The calculated ionization temperatures from the measured flux ratios of different ionization species, measured for Si, S, Ar, Ca, and Fe, with respect to theoretical curves from AtomDB v3.0.9. The legend is the same as Figure 3.7.

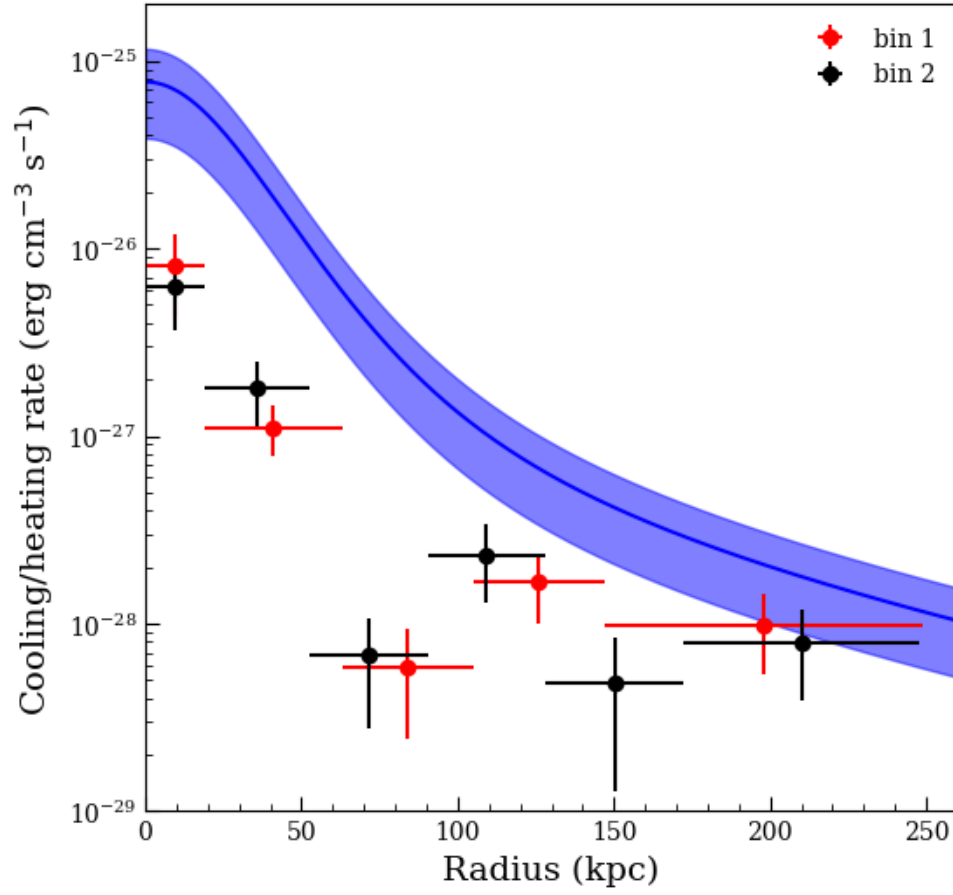


Figure 3.9: Heating vs. cooling rates in each region for both bin layouts. The cooling rate is plotted in blue, with the shaded regions representing $\pm 50\%$ error. The heating rates for each bin layout are plotted as data points in red (bin layout 1) and black (bin layout 2).

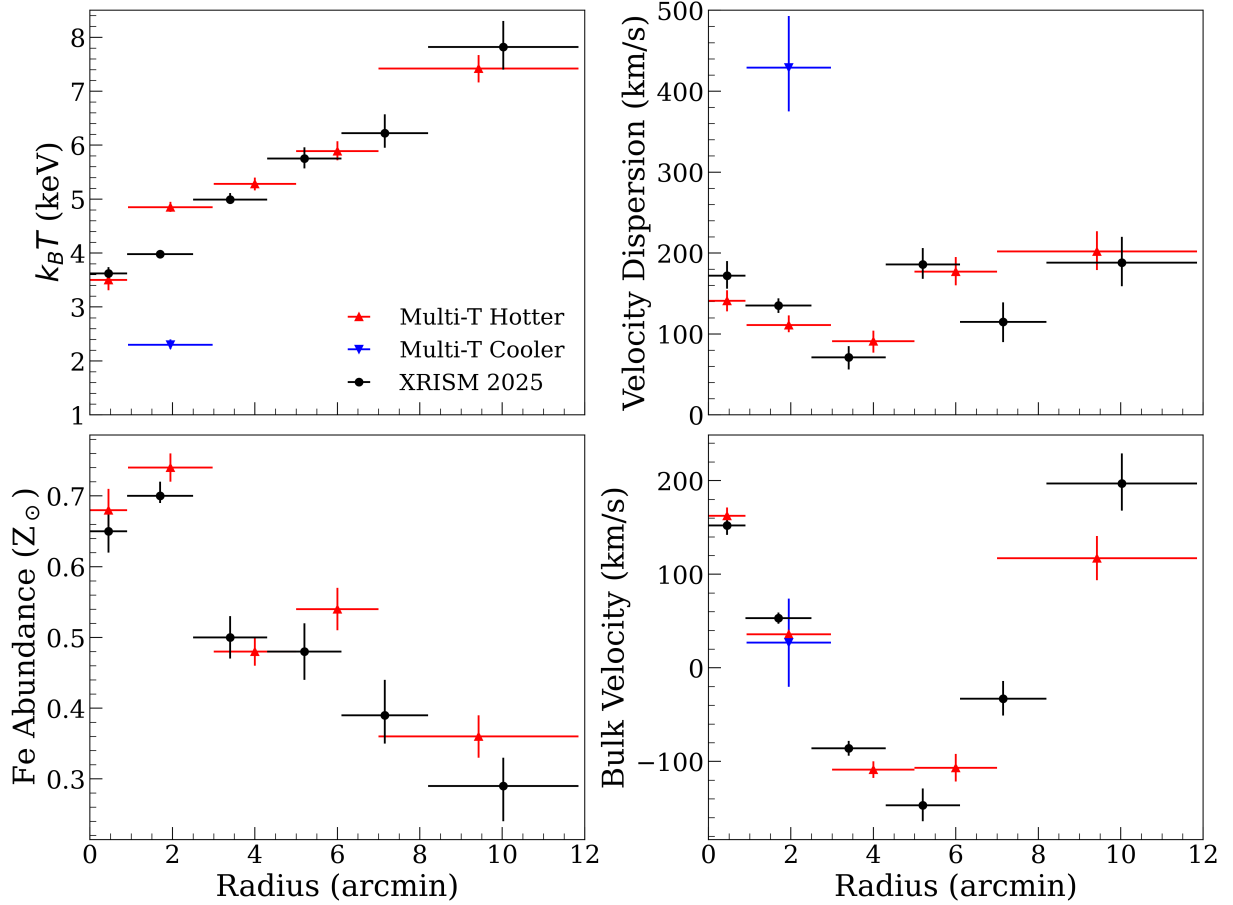


Figure 3.10: Best-fit model measured radial profiles of temperature (top left), velocity dispersion (top right), Fe abundance (bottom left), and bulk velocity (bottom right). The black data points represent the values from the velocity analysis [133]. The red data points represent the values from the single-temperature or hot component of the two-temperature model. The blue data points represent the values from the cold component of the two-temperature model. The bulk velocities are calculated as $v_{\text{bulk}} = c(z - z_{\text{BCG}})/(1 + z_{\text{BCG}})$, relative to the BCG redshift $z_{\text{BCG}} = 0.017284$, with heliocentric correction.

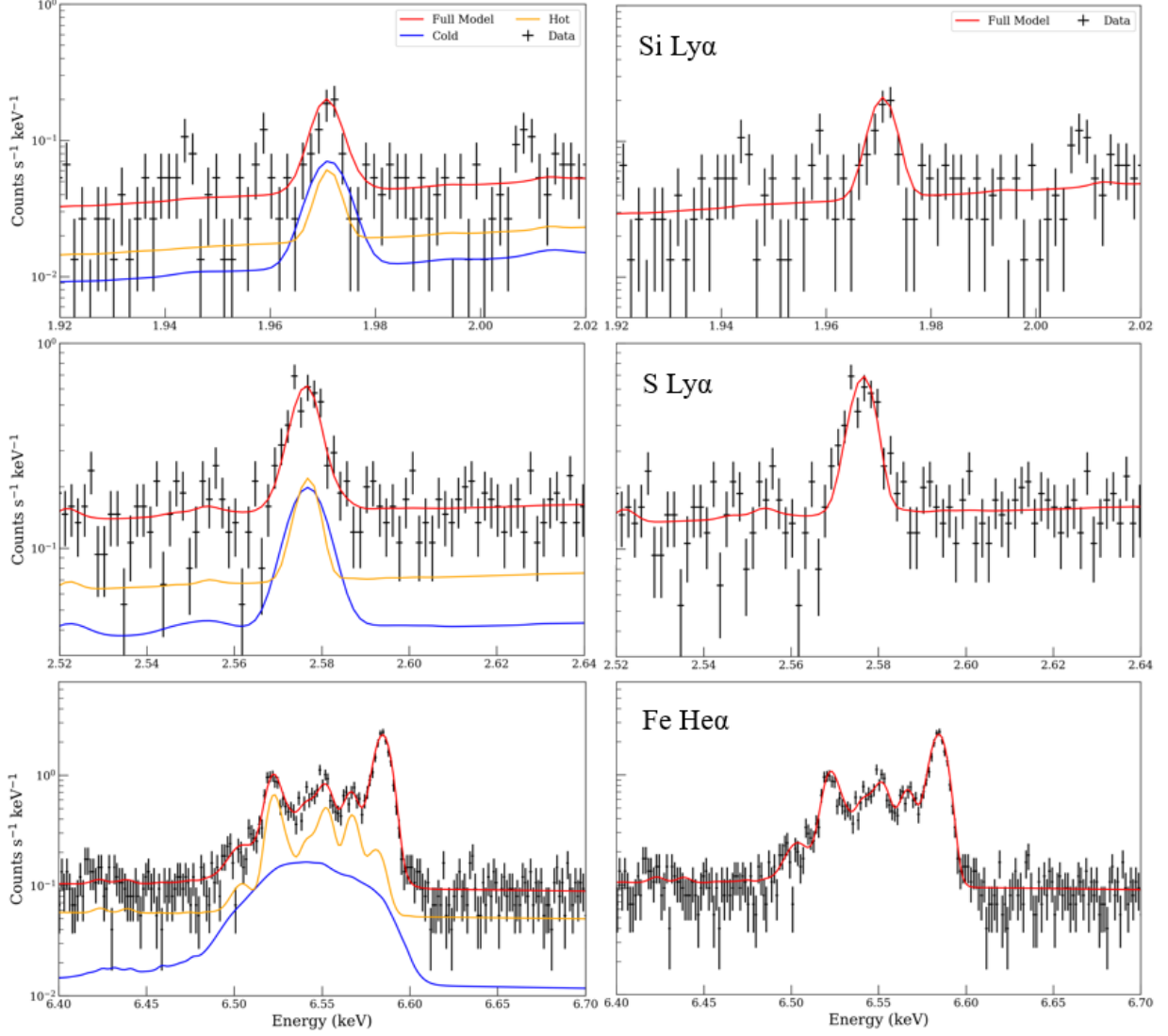


Figure 3.11: Comparison of the region 2 spectrum between the multiple temperature fit with two temperatures in region 2 (left column) and a one-temperature model (right column) for Si xiv Ly α , S xvi Ly α , and Fe xxv He α . The full model for each fit is in red, and the hotter and cooler components of the best-fit two-temperature model are in orange and blue, respectively. The spectrum is re-binned for plotting purposes only. Contributions from the power law, NXB, Fe xxv He α w line gaussian, and scattered photons are not shown.

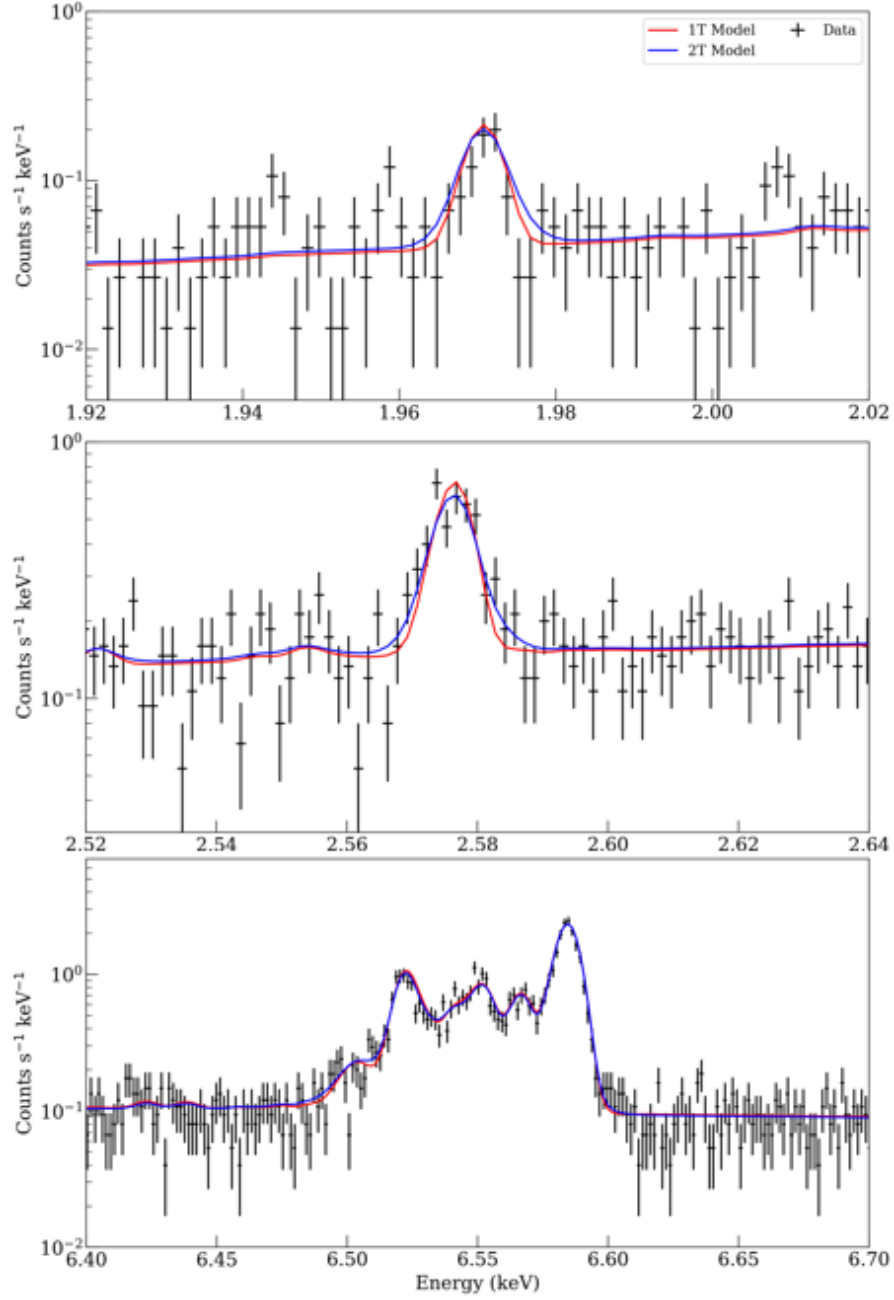


Figure 3.12: The two models from Figure 3.11 compared for Si xiv Ly α , S xvi Ly α , and Fe xxv He α . The one-temperature model is plotted in red, and the multiple temperature model with two temperatures in region 2 is plotted in blue.

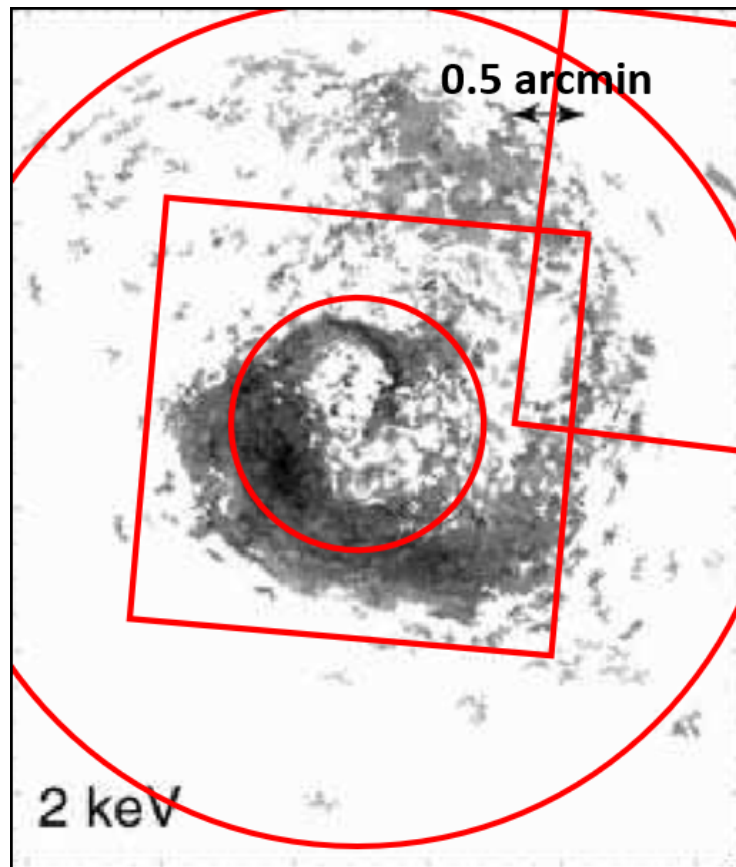


Figure 3.13: Regions 1 and 2 of the multiple temperature analysis, and the C0 and C1 pointings, overlaid on the 2 keV Chandra mass map by A. C. Fabian et al. (2006) [40].

Chapter 4

Hydra A

Some of the contents of this chapter are presented in T. Rose et al. (2025) [103], of which I am a co-author. Details are declared in the Statement of Contributions.

4.1 Introduction

Hydra A is a giant elliptical brightest cluster galaxy (BCG) in the Hydra cluster (Fig. 1.2). It is a textbook radio-mode feedback galaxy, and is one of the most powerful FR1 radio sources [72]. The cluster is a cool core cluster, which accretes over $300 \text{ M}_{\odot} \text{ yr}^{-1}$ [26]. Chandra observations of the cluster show at least three pairs of X-ray cavities from 25 to 200 kpc away from the radio core, ranging in diameter sizes of 40 to 200 kpc, showing a ‘swiss-cheese’-like topology in the intracluster medium (ICM) [132]. The cavities may be merging bubbles generated from a series of AGN outbursts, or connected cavities as a result of a continuously powered AGN over several hundred million years [132]. The BCG hosts a 5 kpc wide disk of molecular gas, which may be providing the fuel to the radio jets of the AGN [100, 101, 102].

The innermost and therefore youngest cavities, found at 25 kpc, are encompassed within the XRISM pointing of Hydra A. Two additional pairs of cavities are found at 60 & 100 kpc and 100 & 225 kpc. These bubbles occupy at least $\sim 10\%$ of the total volume of the cluster within 300 kpc [132]. The bubbles are found within a ‘cocoon shock’, with a Mach number of ~ 1.2 [90]. The bubbles and shocks in Hydra A imply a total work done by the jet of 10^{60} to 10^{61} erg over the last 200–500 Myr, which corresponds to a mean jet power of $\sim 2 \times 10^{45} \text{ erg s}^{-1}$, which is an order of magnitude larger than the Perseus cluster [7, 90, 132]. This

jet power would be sufficient to offset radiative cooling losses corresponding to the $300 M_{\odot} \text{ yr}^{-1}$ accretion rates, as well as heat the gas beyond the cooling region [132].

Until the launch of XRISM, only upper limits on velocity dispersions could be placed using grating spectrographs [109]. As energy dissipation due to turbulence is one of the most prominent candidates for heating the cores of cool core clusters, determining the significance of its role through high resolution spectroscopy is essential. The high jet power of Hydra A, along with the massive cavity system, should serve as a testing ground of the relationship between jet power and the dynamics of the ICM. The high spectral resolution of XRISM Resolve will help place constraints on the velocity dispersion of the gas within the central ~ 93 kpc of the Hydra A cluster, which is a considerable fraction of the ~ 100 kpc cooling region [7], which can probe the impact of jet power on the velocity structure of the ICM.

4.2 XRISM Analysis

The Hydra A observation consists of a single 116.3 ksec pointing, starting November 27, 2024, centered at RA = 9h 18m 5.424s, Dec = $-12^{\circ} 05' 42.36''$ with position angle 114.49° . The calibration pixel, 12, and pixel 27 are ignored in all analysis, as described in previous chapters. The events used are restricted to only the highest quality events. We assume a cluster redshift of $z = 0.0543$. Under the cosmological assumptions defined in chapter 3: a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, this corresponds to a spatial scale of 63 kpc/arcmin.

The XRISM analysis of Hydra A was done with HEASoft 6.34. A large size redistribution matrix file (RMF) was generated with `rs1mkrmf`. Using a 0.5–7 keV Chandra X-ray observation (ObsID: 4970) as a source model, the auxiliary response file (ARF) was generated with `xaarfgen` using a 3×3 arcmin² region with the same pointing parameters to match the XRISM field-of-view, with 1×10^6 photons. Figure 4.1 shows the Chandra image of Hydra A, cropped to the XRISM pointing. Contributions from the non-X-ray background (NXB) are included in the analysis, empirically modeled separately and included as a frozen contribution to the fit.

The full array spectrum was fit with a three-component XSPEC model: `TBabs*baptec + NXB` in both broad band, 1.8–8 keV, and narrowbands, 2.7–4.1, 6.15–6.5, and 7.2–7.65 keV. We use a hydrogen column density of $N_{\text{H}2} = 4.04 \times 10^{20} \text{ cm}^{-2}$ for the line-of-sight through the galaxy, obtained from the HEASARC nH tool [57], which is kept frozen during the fit. We use the `baptec` model for gas in collisional ionization equilibrium (CIE) to

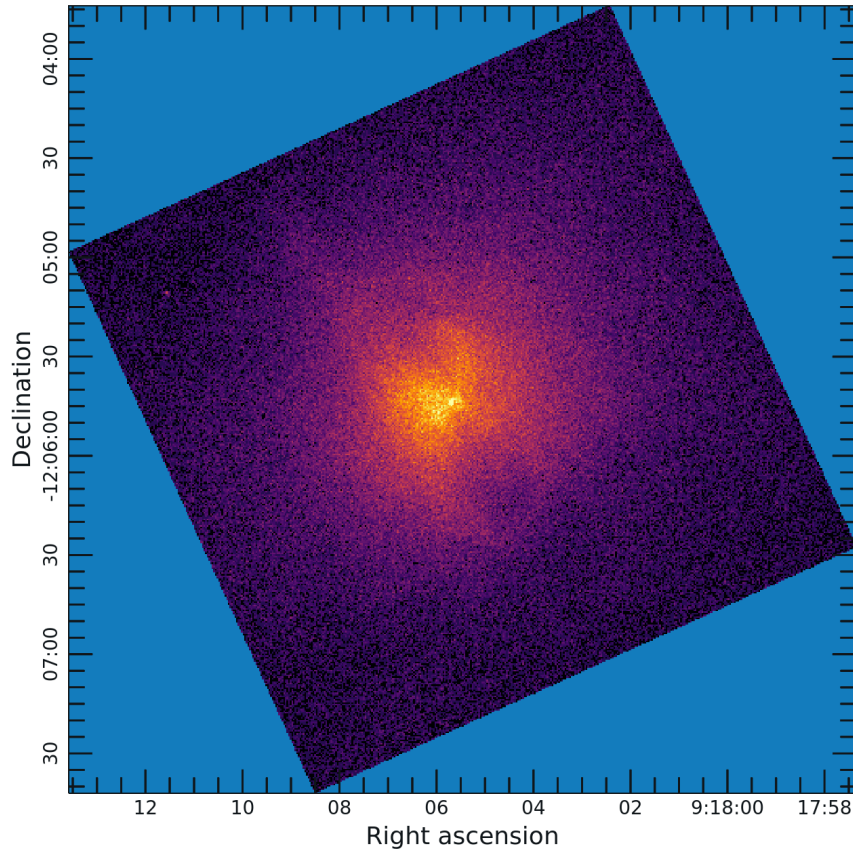


Figure 4.1: Chandra X-ray image of Hydra A, cropped to the XRISM pointing, used for ARF generation [103]. The plot color map is square-root scale.

model contributions from the [ICM](#). The broad band and narrow band fit parameters are provided in table 4.1. The reported redshifts include a heliocentric correction, calculated as $z = z_{\text{fit}} + z_{\text{corr}}$. The heliocentric correction is obtained from measurements calculated with the `barycen` task, which in terms of redshift is $z_{\text{corr}} = 0.00009$.

The broad band spectrum and 1.8–8.0 keV fit are provided in figure 4.2, and the narrow band fits are provided in figure 4.3. We see that the Fe xxv He α complex y intercombination line is not as well fit as the w, x, and z lines. Variations of the narrow band fit were tested excluding the w line, z line, or x & y lines to test the impact of the quality of the fit for each line. Variations in the parameters were 1σ consistent with Table 4.1, but none improved the quality of the fit.

It would be expected that a power law component would be necessary to represent

Parameter	Energy Range (keV)			
	1.8 – 8.0	2.7 – 4.1	6.15 – 6.5	7.2 – 7.65
$k_B T$ (keV)	$3.6^{+0.1}_{-0.1}$	$3.5^{+0.2}_{-0.3}$	$3.34^{+0.21}_{-0.17}$	$2.8^{+0.5}_{-0.4}$
Abundance ($Z_\odot$)	$0.45^{+0.01}_{-0.01}$	$0.42^{+0.08}_{-0.08}$	$0.39^{+0.03}_{-0.03}$	$0.43^{+0.08}_{-0.07}$
Redshift ($\times 10^{-2}$)	$5.421^{+0.005}_{-0.002}$	$5.410^{+0.017}_{-0.014}$	$5.421^{+0.005}_{-0.003}$	$5.434^{+0.012}_{-0.014}$
σ_v (km s $^{-1}$)	164^{+10}_{-10}	146^{+86}_{-92}	160^{+11}_{-10}	154^{+42}_{-35}
Norm	$0.031^{+0.001}_{-0.001}$	$0.032^{+0.003}_{-0.002}$	$0.038^{+0.004}_{-0.004}$	$0.053^{+0.025}_{-0.015}$
C-stat/dof	13833/12393	3026/2795	803/694	1036/893

Table 4.1: Broad and narrow band fit results of the Hydra A spectrum [103].

non-thermal emission from the AGN in the spectral fitting, given the strong AGN point source. Fits were tested with a four component model: `TBabs*(baptec + po) + NXB`. However, including the power law did not improve the statistics of the fit, even with both normalization and photon index free. This experiment was also performed on the narrow band fits, which all showed similar results. A two-temperature model was also tested, however the 1- σ error of some parameters were comparable in magnitude to the parameter values and the fit statistic did not improve, so the two-temperature model was deemed unfit.

We detect a slight excess in the soft band of the spectrum below ~ 2.5 keV (Fig. 4.2). This issue is likely due to effective area uncertainties as a result of the closed gate valve. However, the fits are consistent across broad and narrow bands, which indicates that the soft excess does not severely affect the results.

XRISM Resolve’s large PSF causes photons from different spatial regions in the sky to mix into the same spectrum. This results in measuring photons from outside the instrument’s field of view, which could affect spectral modeling. Significant variations in bulk velocity within Hydra A could be measured as additional velocity dispersion, which would cause the model to overestimate the velocity dispersion, and thus overestimate the turbulent velocity. As the Hydra A data consists of a single pointing, we cannot use spatial-spectral mixing (SSM) to account for photon mixing. The theoretical ray trace simulations from `xrtraytrace` find that only 11% of the photons originate from outside the pointing. Additionally, we measured the fraction of X-ray flux within the XRISM pointing from the reprocessed Chandra data (ObsID:4790), and find that 72% of the X-ray flux originates from within the instrument field-of-view [103]. The inability to constrain a second component, along with these measurements, indicate that the velocity dispersion

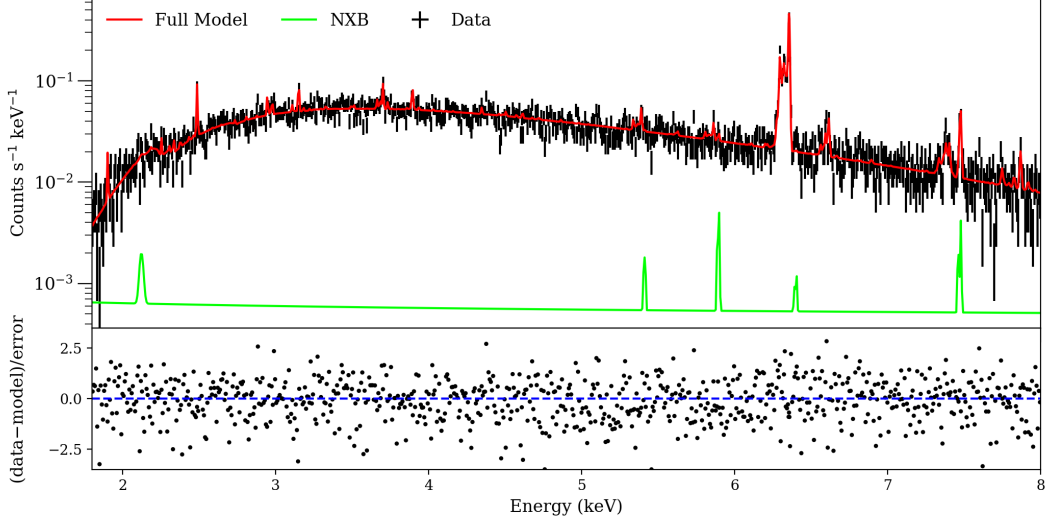


Figure 4.2: Broad band (1.8–8.0 keV) fit of the Hydra-A spectrum reported in table 4.1. The full model is plotted in red, and the NXB is plotted in green. Residuals are plotted in terms of σ below the broad band fit. The spectrum is re-binned for plotting purposes only.

and bulk velocity of the best fit models are likely not subject to large external influences.

4.3 Discussion

4.3.1 Broad vs. Narrow Bands

The narrow band fits report slight differences in temperature, mean abundance, redshift, and velocity dispersion. However, these differences are 1σ consistent with the broad band fit (Table 4.1). The narrow band fit over 6.15–6.5 keV does not fit the Fe xxv He α complex y inter-combination line well (Fig. 4.3), as the observed flux of the Fe xxv He α y line is larger than what the CIE model predicts. This discrepancy is seen in other objects as well (e.g. [84, 133, 134]). However, as noted in section 4.2 the model fits are unaffected by this line.

As expected, the redshift and velocity dispersion of the broad band model align most

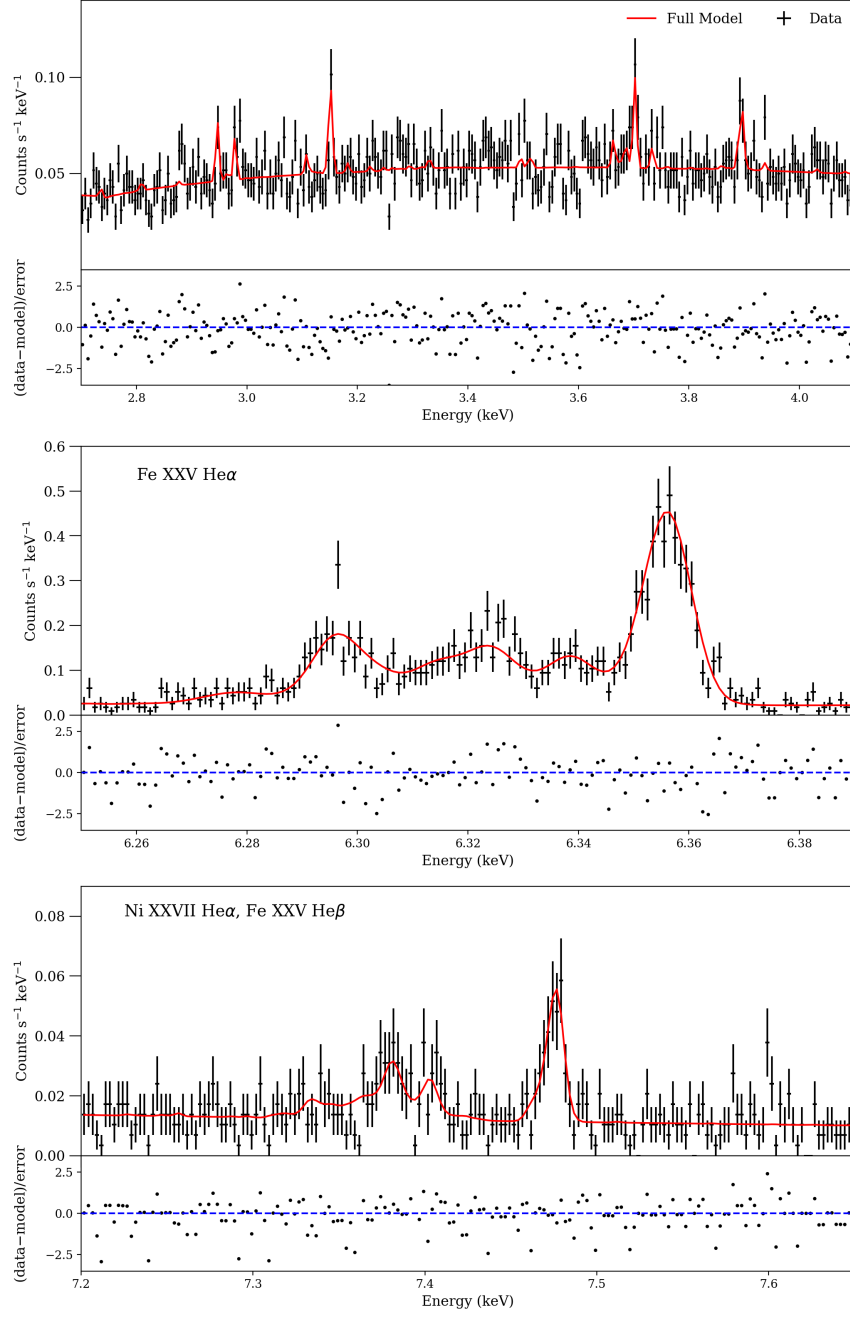


Figure 4.3: Zoomed in plots of narrow band fits reported in table 4.1. The plot information is the same as in figure 4.2. The spectra are re-binned for plotting purposes only.

closely with the 6.15–6.5 keV narrow band fit, since the Fe xxv He α lines are the brightest complex in the spectrum. As these parameters are the most stable in the fits, we explore their properties in the following subsection.

4.3.2 Velocity Structure

We calculate the bulk velocity of the ICM as

$$v_{\text{bulk}} = \frac{c(z - z_{\text{BCG}})}{(1 + z_{\text{BCG}})}, \quad (4.1)$$

where $z_{\text{BCG}} = 0.05434 \pm 0.00005$ is obtained from MUSE measurements using stellar absorption lines at the core of the BCG [100], and z is the heliocentric corrected redshift. With the redshift $z = 5.421_{-0.003}^{+0.005} \times 10^{-2}$ measured from the broadband fit, we calculate a bulk velocity of $v_{\text{bulk}} = -37_{-17}^{+20}$ km s $^{-1}$ for the ICM. This indicates only a small velocity offset between the ICM and the BCG.

The measured velocity dispersion of 164_{-10}^{+10} km s $^{-1}$ is remarkably low for the high jet power of Hydra A, and lower than previous measurements [7, 30, 96]. The sizes of the inner cavities of Hydra A and the Perseus cluster are comparable, while the jet power of Hydra A is an order of magnitude larger than the Perseus cluster [96, 132]. If we assume that turbulence is driven by the jets, we would expect that higher jet powers produce larger velocity dispersions. However, the two clusters share similarly quiescent velocity dispersions of $\lesssim 165$ km s $^{-1}$ [103, 133]. Since Hydra A has multiple pairs of cavities, it is possible that the velocity dispersion rises beyond the spatial region of this pointing, near the other larger cavities. However, the velocity dispersion and bulk velocity measurements reflect the motions of the gas in the inner ~ 93 kpc, which is where we would expect to see high velocity dispersions.

4.3.3 Energetics

The XRISM pointing covers up to a radius of ~ 93 kpc from the cluster center. We estimate the gas mass to be $M \simeq 1.5 \pm 0.1 \times 10^{12}$ M $_{\odot}$ [103]. If we assume that the velocity dispersion is due to purely isotropic turbulence, we can estimate the power injected into the ICM within this region as

$$\dot{E} \simeq \frac{3}{2} \frac{M v_{\text{turb}}^3}{l_{\text{eff}}}, \quad (4.2)$$

where $l_{\text{eff}} \simeq 78$ kpc is the effective scale in which the power is injected [103]. We assume an effective scale as the true injection scale is not known [103]. We assume that the velocity dispersion is the turbulent velocity. However, the velocity dispersion is likely not purely due to turbulence, so this is an upper limit.

For a velocity dispersion of 164^{+10}_{-10} km s⁻¹, this corresponds to an injected power of $\lesssim 8.2 \pm 1.5 \times 10^{43}$ erg s⁻¹ due to turbulence. The cooling luminosity of the cooling region (central ~ 100 kpc) of Hydra A is $2.5 \pm 1.5 \times 10^{44}$ erg s⁻¹ [7, 30, 96], which is roughly three times larger than the calculated injected energy. As this heating rate is an upper limit, this implies that heat dissipation due to turbulence would struggle to balance cooling in Hydra A. However, as noted it is possible that the velocity dispersion, and thus turbulence and heating due to turbulence, is higher near the larger cavities. Analysis of the outer regions is necessary to further develop our understanding of heating due to turbulence in Hydra A.

4.4 Summary

We present an analysis of the XRISM Resolve observation of the Hydra A cluster. We performed spectral fitting, modeling the intracluster medium as a single temperature gas in collisional ionization equilibrium, to derive the temperature, mean metal abundance, velocity dispersion, and bulk velocity in the inner ~ 93 kpc of the cluster.

Small variations are observed between the broad and narrow band fits, however they are all consistent. The broad band fit and the narrow band fit of the Fe xxv He α lines, the brightest in the spectrum, are consistent, suggesting that the measurements are robust. We measure a 3.6 keV gas with a small velocity offset with respect to the central galaxy, with a remarkably low velocity dispersion of 164^{+10}_{-10} km s⁻¹. This implies a relatively quiescent state of the gas, in contrast to the expectations from Hydra A’s high jet power and massive cavity structure. This suggests that the velocity structure of the intracluster medium may not have a strong relationship with the jet power. However, it is possible that the velocity dispersion rises near the larger cavities, which are not within the XRISM pointing. Observations of the outer regions of the cluster are needed to fully understand the velocity structure of the intracluster medium in Hydra A.

Chapter 5

Cygnus A

Some of the contents of this chapter are presented in A. Majumder et al. (2025) [76], of which I am a co-author. Details are declared in the Statement of Contributions.

5.1 Introduction

Cygnus A is a giant elliptical brightest cluster galaxy (BCG) in the Cygnus A cluster. It is a FR II radio galaxy, and is one of the brightest radio sources in the sky at its redshift [19, 41]. It features a powerful radio jet, ejecting an estimated $\sim 10^{60}$ erg of energy over the last $\sim 2 \times 10^7$ yr [117]. The estimated average jet power is $\sim 10^{46}$ erg s $^{-1}$, which makes Cygnus A the nearest powerful radio galaxy [52, 117]. The galaxy is embedded in a dense ($\sim 2 \times 10^{-2}$ cm $^{-3}$) intracluster medium that is cooling at a rate of ~ 100 M $_{\odot}$ yr $^{-1}$, which is feeding the AGN [2, 3, 18].

The jets are creating large radio lobes, ending in hot spots on the Western and Eastern sides, resulting in large X-ray cavities in the intracluster medium (ICM) seen in in Figure 5.1. This large output of energy from the jets and lobes into the ICM generated a large cocoon shock, featuring Mach numbers of $\sim 1.18 - 1.66$ [117]. These shocks have velocities up to ~ 1600 km s $^{-1}$, with the hot spots moving even faster, up to ~ 4000 km s $^{-1}$.

Between the cocoon shocks, large radio lobes and X-ray cavities, and powerful jets, Cygnus A presents potentially one of the most extreme ICM environments. Therefore, we would expect to measure relatively high velocity dispersions in the ICM. This makes Cygnus A an exciting object to observe with XRISM, to further study how the velocity structure of the ICM is affected by such extreme conditions.



Figure 5.1: Composite image of Cygnus A, showing X-rays (blue) and optical (yellow). Large X-ray cavities and hot spots are seen on the Western and Eastern sides, which are enveloped in the cocoon shock structure that surrounds the central galaxy. Credit: X-ray: NASA/CXC/Columbia Univ./[65]; Optical: NASA/STScI.

5.2 XRISM Analysis

The Cygnus A observation is a single 170 ksec pointing starting on October 6th 2025, centered at $\text{RA} = 19^{\text{h}}59^{\text{m}}29.36^{\text{s}}$, $\text{Dec} = 40^{\circ}44'01.6''$, with position angle 275.39° . The calibration pixel and pixel 27 are ignored in all analysis. The events used are restricted to only the highest quality events. We assume a cluster redshift of $z = 0.05608 \pm 0.00007$ [91]. Under the cosmological assumptions defined in Chapter 3: a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, this corresponds to a spatial scale of 65 kpc/arcmin.

The XRISM analysis of Cygnus A was done with HEASoft 6.34. We used an extra-large size redistribution matrix file (RMF) generated with `rs1mkrmf`. The auxiliary response file (ARF) was generated in image mode using a 0.5–7 keV Chandra X-ray observation (ObsID: 360) as a source model, using 1×10^6 photons. The region is a $5'$ diameter circular region centered at the same pointing parameters as the XRISM observation, shown in figure 5.2. This choice of ARF includes contributions from beyond the field of view to account for photon scattering due to XRISM’s large PSF. The non-X-ray background (NXB) is empirically modeled separately, and included as a frozen contribution to the fit. The spectrum is re-binned with the `ftgrouppha` task to a minimum of 1 count per bin.

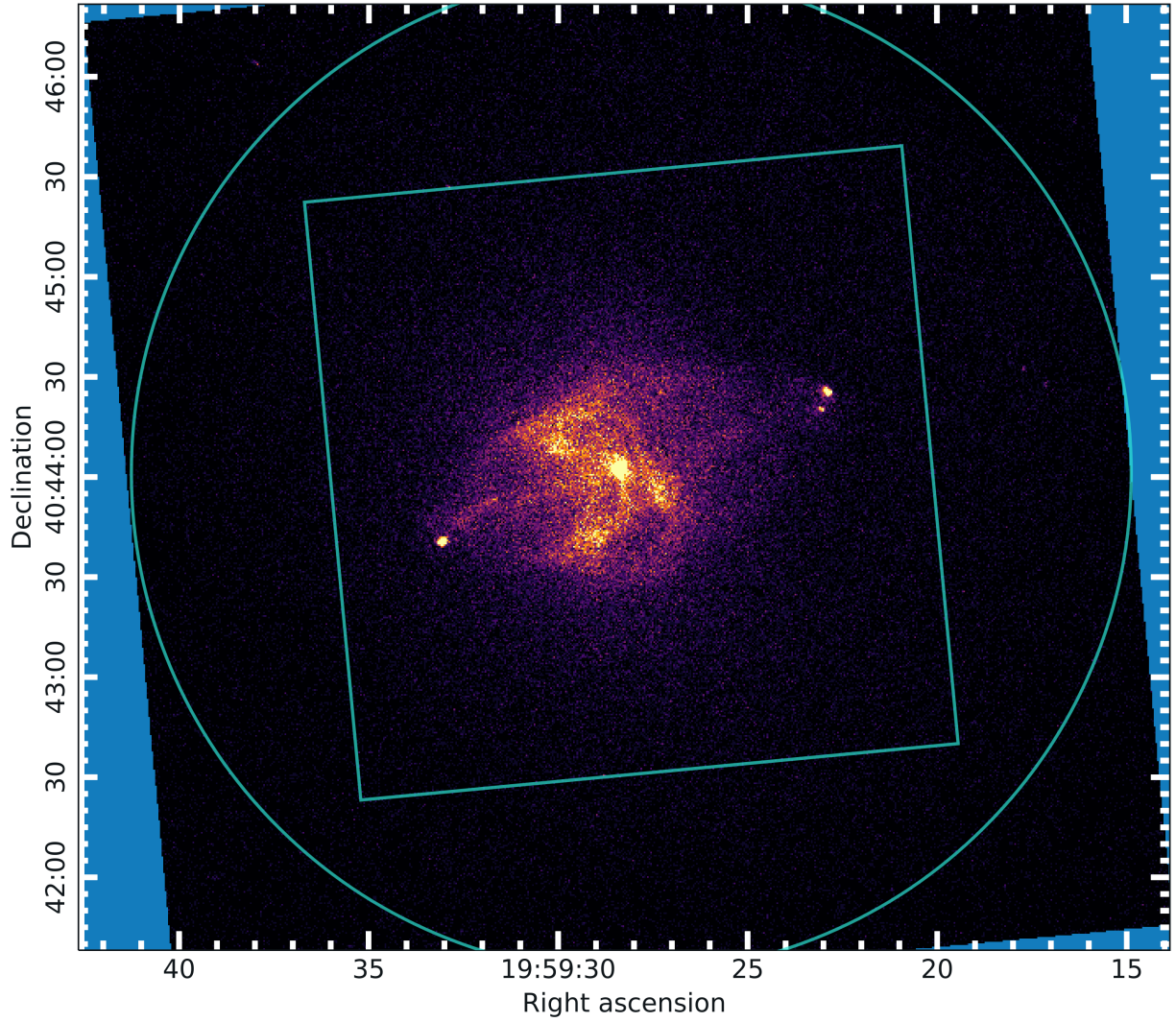


Figure 5.2: The XRISM pointing (square) and source ARF region (circle) of Cygnus A overlaid on the 0.5–7.0 keV Chandra image [76]. The color map is a square-root scale.

We fit the broadband over 1.7–12 keV, with a five component one-temperature model: `TBabs*bvapec + TBabs*powerlaw + NXB`. We model the **ICM** with `bvapec` to model a **CIE** gas. We model non-thermal contributions to the spectrum (e.g. the **AGN**) with `powerlaw`. We use the **TBabs** Tuebingen-Boulder absorption model to represent X-ray absorption by the interstellar medium. The power law and **CIE** components are absorbed with different column densities since the **AGN** is more heavily obscured than the **ICM**, as indicated by the Fe absorption edge [76, 137], and thus it is expected to have a significantly higher column density along the line of sight than the **ICM**, since the **ICM** extends far beyond the central galaxy. The abundances of Si, S, Ar, Ca, Fe, and Ni are left free, with the other metals frozen at Solar values.

Unlike the spectra from Perseus (Chapter 3) and Hydra A (Chapter 4), this spectrum has two additional significant spectral features. At ~ 6.1 keV, a narrow nuclear fluorescent Fe $K\alpha$ line (6.4 keV rest frame energy), as well as a nuclear Fe absorption edge (7.2 keV rest frame energy) between Fe xxvi Ly α and Fe xxv He β . The fluorescent Fe line is due to irradiation from Fe II-XVIII in the circumnuclear gas around the **AGN** [76, 137]. The Fe absorption edge is due to the K-shell edge of Fe I-X [137]. Since this analysis is focused on the **ICM**, we chose to remove the Fe $K\alpha$ fluorescent line (6–6.125 keV) and the Fe iron dip (6.75–7.2 keV) from the spectrum, to avoid any influence from these features on the `bvapec` component. Additionally, the Fe xxv He α w line (6.325–6.375 keV) is ignored to avoid inconsistencies with the **CIE** model due to resonant scattering. The Si He β line (2.220–2.265 keV) is ignored as it lies exactly at the Si edge of the **ARF** which caused issues during fitting [76]. The Si fluorescent line (1.735–1.750 keV) is also ignored as spectral fitting was unable to successfully fit this line, likely due to calibration issues [76]. The parameters of the model fit are provided in table 5.1.

The full array spectrum and one-temperature model fit, along with the separate contributions from the **CIE**, **AGN**, and **NXB**, are provided in figure 5.3. We see large residuals at the fluorescent Fe line and the Fe edge, but this is expected as these features are not included in the fit. Figures 5.4 & 5.5 show zoomed in plots of the spectrum focused on several prominent emission lines. The fluorescent Si line and attenuated Si He β line are not shown. We show the fluorescent Fe line, Fe absorption edge, and Fe xxv He α w line, but they are not included in the fit. We see that there is a discrepancy between the observed fluxes of Fe xxv He α z and inter-combination lines and the **CIE** model, despite accounting for resonant scattering, as seen in other objects (e.g. [84, 134]). Removing or including different subsets of the w, x, y, and z lines did not improve the quality of the fit or the fit statistics. We see that some of the lower energy emission lines of Si–Ca are not as well fit as the Fe lines, and that the model reports consistently potential super-solar abundance ratios with respect to Fe, which may indicate the existence of a cooler component, as abun-

Table 5.1: Broad band fit results of the five component one-temperature model over 1.7–12 keV. The model details are provided in section 5.2. Errors are statistical 1σ errors. The fit Cstat/dof = 16696/17454.

Parameter	Value
$N_{\text{H}^2; \text{CIE}} (\times 10^{-21} \text{ cm}^{-2})$	0.414
$k_B T$ (keV)	$5.19^{+0.10}_{-0.09}$
Si Abund. ($Z_\odot$)	$1.19^{+0.27}_{-0.24}$
S Abund. ($Z_\odot$)	$0.83^{+0.10}_{-0.09}$
Ar Abund. ($Z_\odot$)	$0.74^{+0.12}_{-0.12}$
Ca Abund. ($Z_\odot$)	$0.72^{+0.11}_{-0.10}$
Fe Abund. ($Z_\odot$)	$0.60^{+0.02}_{-0.02}$
Ni Abund. ($Z_\odot$)	$0.76^{+0.12}_{-0.11}$
$z (\times 10^{-2})$	$5.648^{+0.005}_{-0.006}$
σ (km s $^{-1}$)	272^{+14}_{-13}
Norm _{CIE} ($\times 10^{-2}$)	$4.68^{+0.06}_{-0.06}$
$N_{\text{H}^2; \text{AGN}} (\times 10^{-21} \text{ cm}^{-2})$	$34.23^{+1.59}_{-1.55}$
Γ	$1.99^{+0.05}_{-0.05}$
Norm _{AGN} ($\times 10^{-2}$)	$3.45^{+0.44}_{-0.39}$

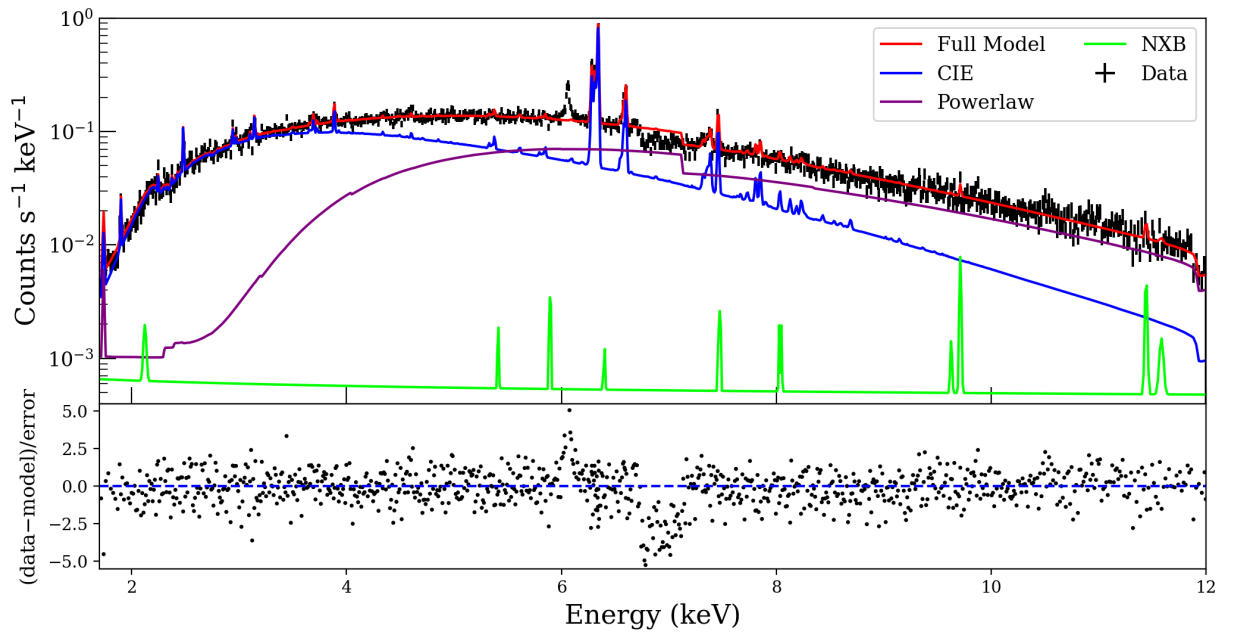


Figure 5.3: Broad band plot of the five component one-temperature model of the Cygnus A spectrum over 1.7–12 keV. The residuals are plotted in terms of σ . Model details are provided in section 5.2. The spectrum is binned for plotting purposes.

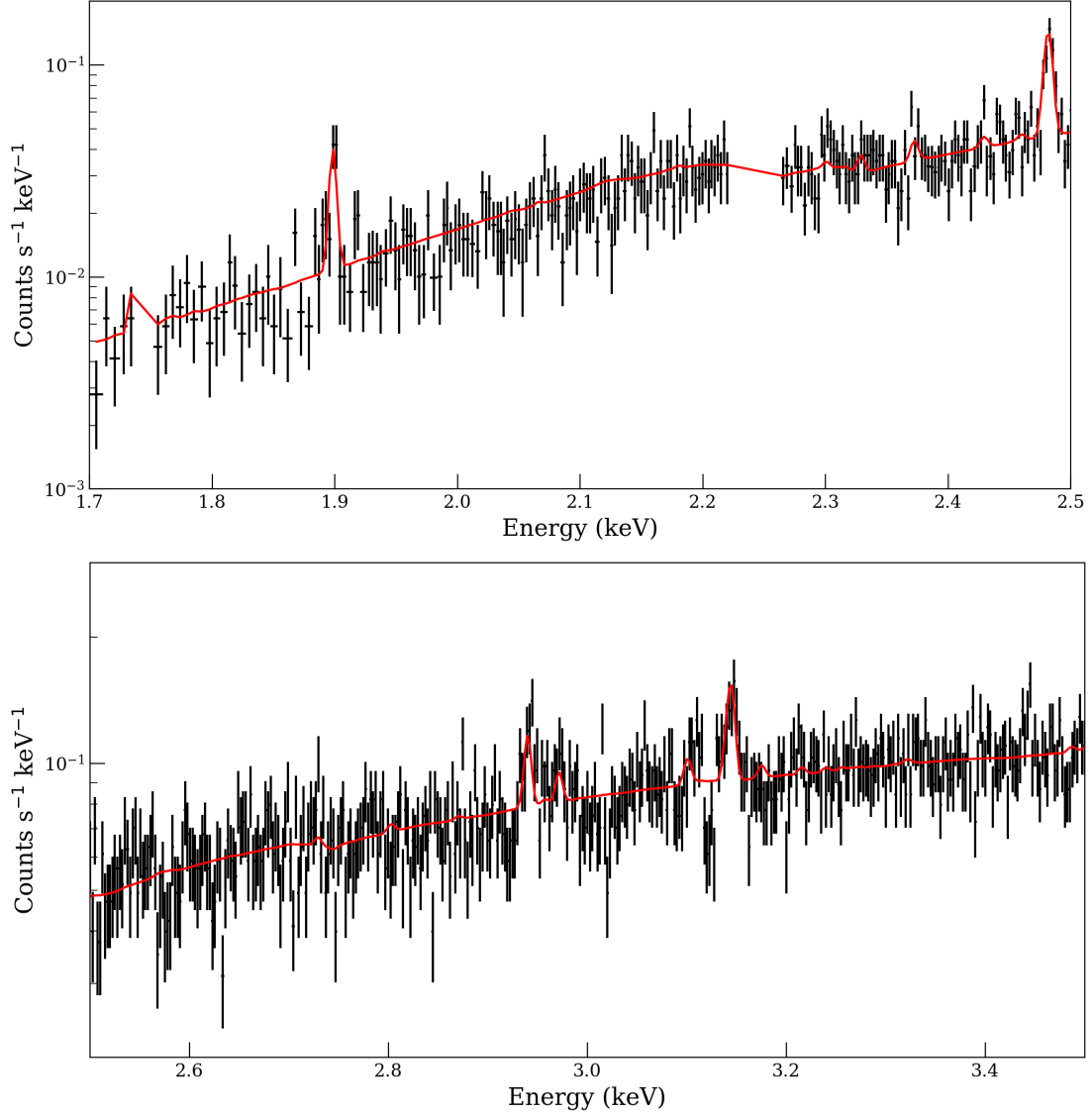


Figure 5.4: Narrow band plots of the five component one-temperature model of the Cygnus A spectrum over 1.7–2.5 and 2.5–3.5 keV. Model details are provided in section 5.2. Only the full model is shown. The fluorescent Si line and the attenuated Si He β line are removed from the plot. The spectra are binned for plotting purposes.

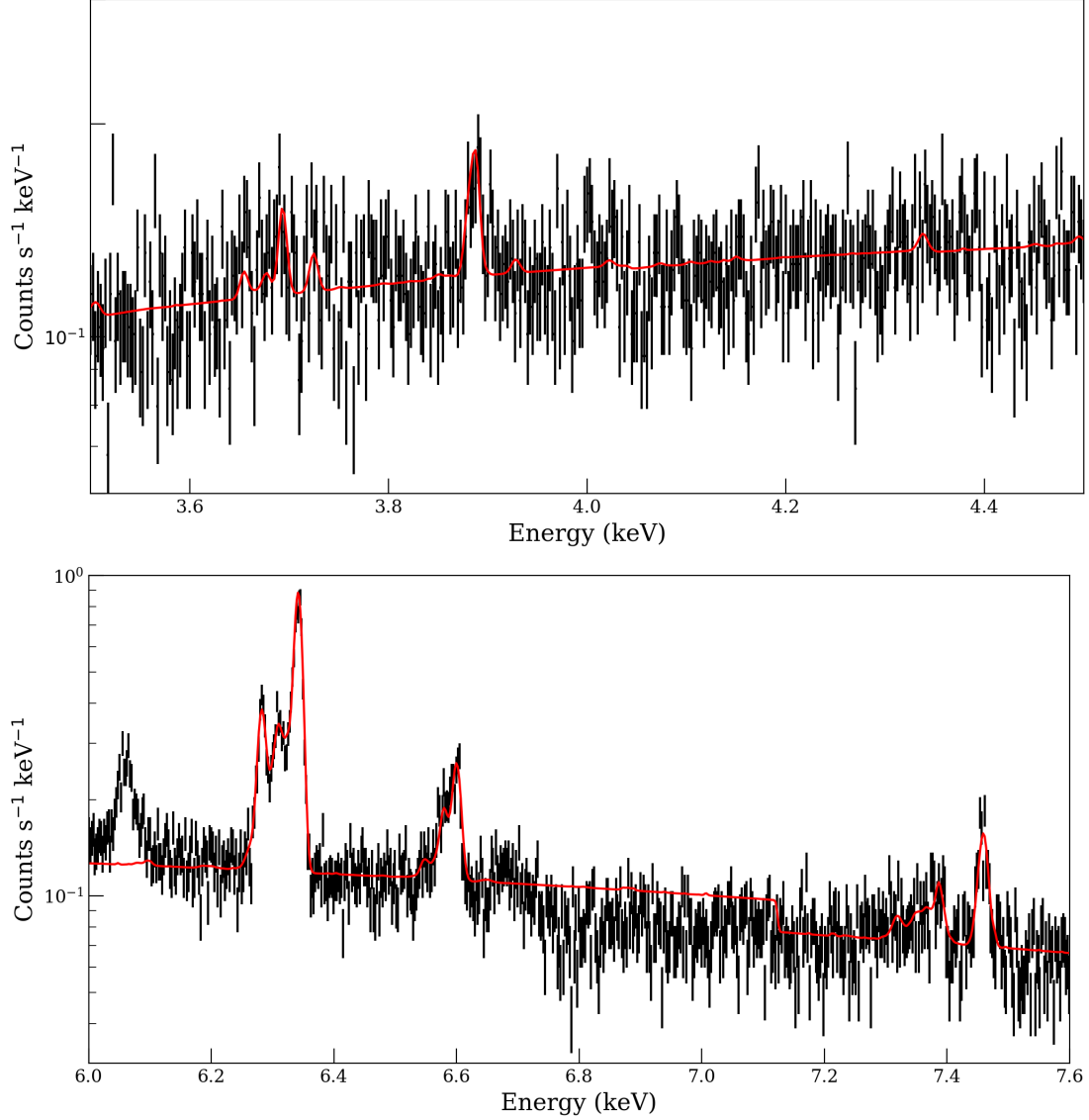


Figure 5.5: Narrow band plots of the five component one-temperature model of the Cygnus A spectrum over 3.5–4.5 and 6–7.6 keV. Model details are provided in section 5.2. Only the full model is shown. The fluorescent Fe line, Fe absorption edge, and Fe xxv He α w line are shown, but are not included in the fit. The spectra are binned for plotting purposes.

dances from Si and S may be inflated to adjust for emission from a cooler gas component unaccounted for in the single temperature model [76].

Over the 1.7–12 keV band, removing the same spectral features as in the single temperature model, we fit a six component two-temperature model: `TBabs*(bvappec + bvappec) + Tbabs*powerlaw + NXB`, in order to address the poor fits of the lower energy emission lines. The abundances of Si, S, Ar, Ca, Fe, and Ni between the two components are tied, while the temperatures, redshifts, velocity dispersions, and normalizations of the two components are left free to vary independently [76]. The model fit results are provided in Table 5.2. We find that the two-temperature model prefers a cooler, broader second component with a significant redshift offset relative to the first component.

We find a decrease in the C-stat of 20, however the two-temperature model has 4 more parameters than the one-temperature model. We can determine if the two-temperature model is statistically significant by employing the Akaike Information Criterion (AIC) [76], given by

$$\text{AIC} = 2k - 2 \ln \hat{L}, \quad (5.1)$$

$$= 2k + \text{C-stat (eq. 2.3)}. \quad (5.2)$$

The reason we chose to use the AIC for Cygnus A instead of the BIC, like in the Perseus cluster (section 3.2.3), is because the data constitutes only a single pointing. The processed Cygnus A spectrum has fewer bins, roughly 10 times less total bins compared to the Perseus data (Chapter 3). Therefore, the penalization factor of the AIC is sufficient. Similarly to the BIC, the difference in AIC between the one-temperature and two-temperature models can indicate the significance of introducing a second temperature component to the fit. We find a $\Delta\text{AIC} = 12$ between the two models, favoring the two-temperature model.

The full array spectrum and two-temperature model fit, showing separate contributions from both CIE components, the AGN, and the NXB, are shown in figure 5.6. The hotter component is the dominant CIE component, plotted in blue, while the cooler component is the non-dominant CIE component, plotted in orange. Figure 5.7 shows zoomed-in plots of two of the lower energy emission lines, specifically Si xiv Ly α , S xv Ly α [76], as well as Fe xxv He α . Only the spectrum, full model (red), and separate contributions from the hotter (orange) and cooler (blue) components are plotted. We see asymmetric structure in the lower energy emission lines, seen most clearly in S xv Ly α . Just like in the Perseus cluster, the effect of the cooler component is most evident in S xv Ly α , where the hotter component takes the dominant narrower section at lower energies (higher redshift), while the cooler component adds the broader section at higher energies (lower redshift) [76]. This effect is also seen with Si xiv Ly α , but not as obvious. We also look at the complex of

Table 5.2: Broad band fit results of the six component two-temperature model over 1.7–12 keV. The model details are provided in section 5.2. Errors are statistical 1σ errors. The fit Cstat/dof = 16676/17450.

Parameter	Value (Comp. 1)	Value (Comp. 2)
$N_{\text{H}^2; \text{CIE}} (\times 10^{-21} \text{ cm}^{-2})$	0.414	—
$k_B T$ (keV)	$5.39^{+0.20}_{-0.11}$	$2.06^{+0.43}_{-0.20}$
Si Abund. ($Z_\odot$)	$0.87^{+0.21}_{-0.20}$	—
S Abund. ($Z_\odot$)	$0.71^{+0.10}_{-0.09}$	—
Ar Abund. ($Z_\odot$)	$0.75^{+0.12}_{-0.11}$	—
Ca Abund. ($Z_\odot$)	$0.75^{+0.11}_{-0.11}$	—
Fe Abund. ($Z_\odot$)	$0.63^{+0.02}_{-0.02}$	—
Ni Abund. ($Z_\odot$)	$0.80^{+0.13}_{-0.13}$	—
$z (\times 10^{-2})$	$5.655^{+0.005}_{-0.006}$	$5.494^{+0.041}_{-0.041}$
σ (km s $^{-1}$)	261^{+14}_{-14}	333^{+127}_{-129}
$\text{Norm}_{\text{CIE}} (\times 10^{-2})$	$4.09^{+0.18}_{-0.33}$	$0.83^{+0.37}_{-0.24}$
$N_{\text{H}^2; \text{AGN}} (\times 10^{-21} \text{ cm}^{-2})$	$32.17^{+1.59}_{-1.47}$	—
Γ	$1.99^{+0.05}_{-0.05}$	—
$\text{Norm}_{\text{AGN}} (\times 10^{-2})$	$3.47^{+0.42}_{-0.38}$	—

Fe xxv He α emission lines, and see that the cooler component captures the broader wing in the Fe xxv He α w line at ~ 6.37 keV, despite this line not being included in the fit. However, we see that the Fe xxv He α z and inter-combination lines are still undershot by the full model.

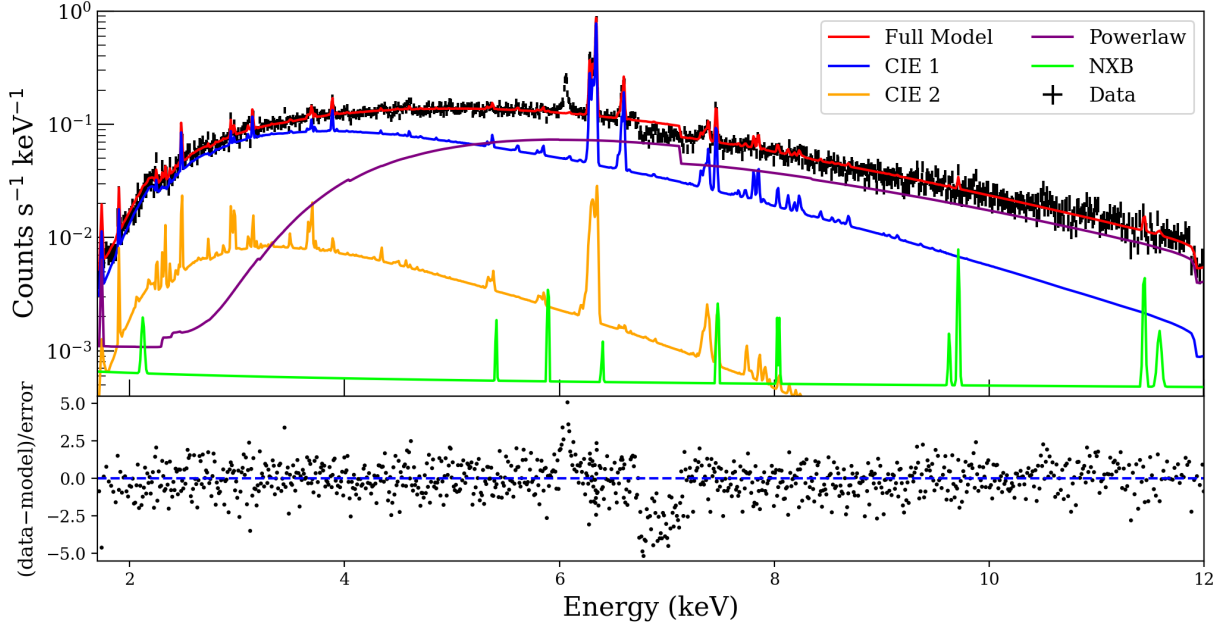


Figure 5.6: Broad band plot of the six component two-temperature model of the Cygnus A spectrum over 1.7–12 keV. The residuals are plotted in terms of σ . Model details are provided in section 5.2. The spectrum is binned for plotting purposes.

5.3 Discussion

5.3.1 Single Temperature Model

The five component one-temperature fit provides solid constraints on a single temperature CIE gas. The measured velocity dispersion is $\sigma = 272^{+14}_{-13}$ km s $^{-1}$, which is larger compared to the unexpectedly low dispersions measured in other objects [103, 133]. We see that the ICM is redshifted compared to the BCG, and calculate the heliocentric corrected bulk velocity (eq. 4.1) to be 101 ± 26 km s $^{-1}$. The heliocentric correction is obtained with the `barycen` task, which reports -13 km s $^{-1}$.

Assuming that this gas represents the kinematics of the ICM, we can calculate the dynamics. We calculate the sound speed (eq. 3.7), with $k_B T = 5.19^{+0.10}_{-0.09}$ keV, to be $c_s = 1165^{+11}_{-36}$ km s⁻¹. The measured velocity dispersion, $\sigma = 272^{+14}_{-13}$ km s⁻¹, is low compared to the sound speed. We calculate the 3D Mach number (eq. 3.8), assuming that the velocity dispersion is purely due to isotropic turbulence, to be $M_{3D} \simeq 0.40 \pm 0.02$. We then calculate the non-thermal pressure fraction (eq. 3.9) to be $\sim 8.3 \pm 0.8\%$. These numbers are consistent with the low non-thermal pressure fractions in other objects (e.g. [49, 133]). The measured velocity dispersion is likely not purely turbulence, and may also be motion of the cocoon shock [76], so these values are upper limits.

5.3.2 Two-Temperature Model

The two-temperature model suggests a cooler second component that is offset in redshift from the hotter component, and has a slightly higher velocity dispersion. While the AIC statistic indicates that the cooler component is significant, the uncertainties on the parameters, particularly velocity dispersion, are very large. Additionally, the normalization of the cooler component is relatively low. The large uncertainties make it challenging to determine the significance of the cooler component. Systematic effects (e.g. abundance tables, energy scale offset) place additional uncertainty on the significance of the cooler component.

Closer inspection of the Si xiv Ly α , S xv Ly α , and Fe xxv He α emission lines (Fig. 5.7) reveal asymmetric broad structure that may not be explained by a single CIE component [76]. This structure is accounted for with the two-temperature model, as the two components fit the lines with a redshift offset and higher dispersion in the cooler component. This effect is most evident in with S xv Ly α , but it also visible in the other lines. This may indicate that the cooler component is real, but due to the other uncertainties it is not clear if it is real.

Assuming the cooler component is real, we can calculate its dynamics, albeit with large uncertainties. We calculate the sound speed (eq. 3.7) of the cooler gas component, with $k_B T = 2.06^{+0.43}_{-0.20}$ keV, to be $c_s = 734^{+77}_{-36}$ km s⁻¹. The measured velocity dispersion, $\sigma = 333^{+127}_{-129}$ km s⁻¹, is comparable to the sound speed. We calculate the 3D Mach number (eq. 3.8), assuming that the velocity dispersion is purely due to isotropic turbulence, to be $M_{3D} \simeq 0.79 \pm 0.31$ for the cooler component, which is high compared to the hotter component ($\sim 0.38 \pm 0.02$). We then calculate the non-thermal pressure fraction (eq. 3.9) to be $\sim 25.5 \pm 15.0\%$, which is larger than the hotter component ($\sim 7.4 \pm 0.8\%$). As noted in section 5.3.1, the measured velocity dispersion is likely a combination of turbulence and

motion of the cocoon shock [76], so we these values are upper limits. The two-temperature model suggests that the hotter component is redshifted with respect to the BCG, and that the cooler component is blueshifted. We calculate heliocentric corrected bulk velocities (eq. 4.1) of $120 \pm 26 \text{ km s}^{-1}$ for the hotter component, and $-311 \pm 118 \text{ km s}^{-1}$ for the cooler component.

5.4 Summary

We present an analysis of the XRISM Resolve observation of the Cygnus A cluster. We performed spectral fitting with single and multiple temperature models of a gas in collisional ionization equilibrium to derive the temperature and velocity structure of the intracluster medium, as well as abundances of Si, S, Ar, Ca, Fe, and Ni, in the inner $\sim 98 \text{ kpc}$ of the cluster.

With the single temperature modeling, we find a $5.19_{-0.09}^{+0.10} \text{ keV}$ gas that is redshifted with respect to the central galaxy. We measure a high velocity dispersion of $272_{-13}^{+14} \text{ km s}^{-1}$, which is higher than the Perseus and Hydra A clusters. The velocity dispersion and bulk velocity likely reflect a mixture of turbulence in the core as well as motion of the cocoon shock [76], however the upper limit on the non-thermal pressure fraction is consistent with other objects. Additionally, the model suggests potentially super-solar abundance ratios with respect to Fe, albeit with large uncertainties.

The two-temperature model suggests a potentially significant second temperature component. This component suggests a $2.06_{-0.20}^{+0.43} \text{ keV}$ gas with $333_{-129}^{+127} \text{ km s}^{-1}$ velocity dispersion, that is blueshifted with respect to the central galaxy with a bulk velocity of $-311 \pm 118 \text{ km s}^{-1}$. This suggests a cooler gas with a high 3D Mach number ($\sim 0.79 \pm 0.31$) and non-thermal pressure fraction ($\sim 25.5 \pm 15.0\%$). Close inspection of the prominent emission lines Si xiv Ly α and S xv Ly α in the soft band, and the Fe xxv He α complex, suggest that the two-temperature model accurately fits asymmetric broad features in these emission lines. However, the large uncertainties in the parameters, as well as other systematic effects, suggest that this component may not be significant.

Deeper observations of the Cygnus A cluster are necessary to get a better understanding of the velocity structure of the intracluster medium. As the gas motions likely reflect a combination of turbulence and motion of the cocoon shock, it would be beneficial to better understand the one- and two-temperature components, particularly the significance of the cooler component, and their dynamics.

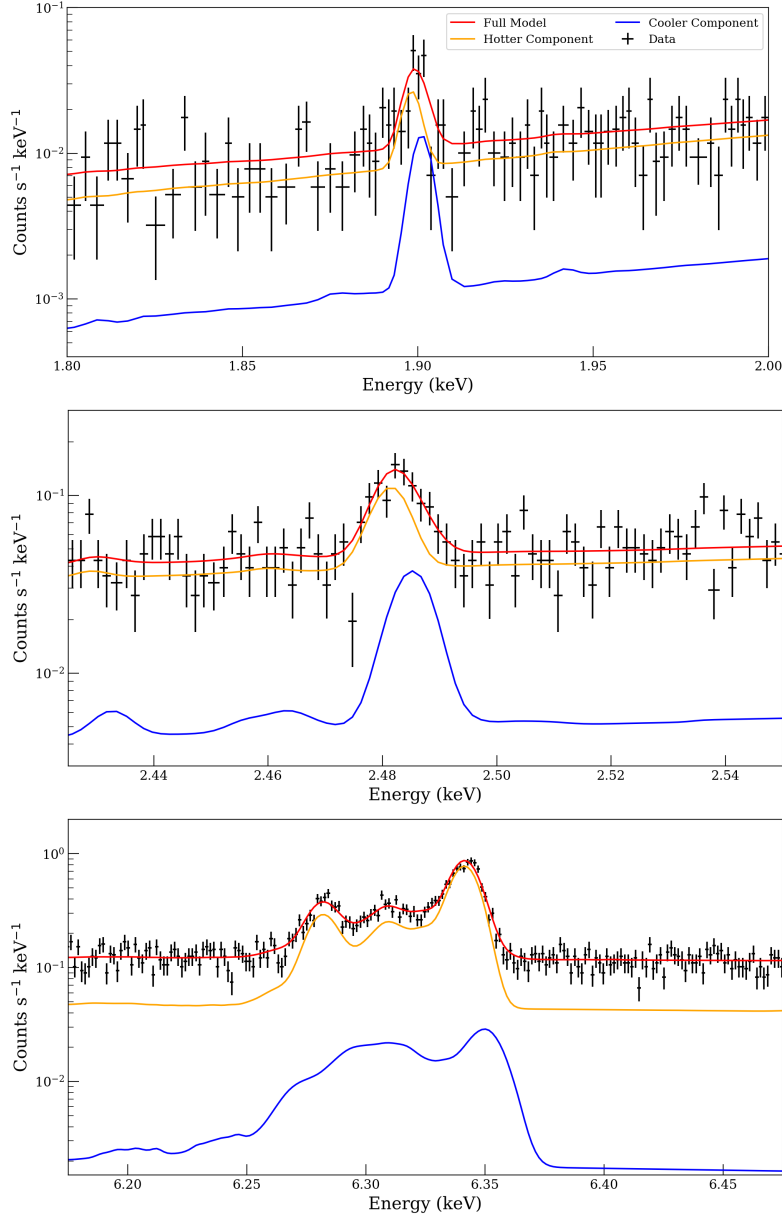


Figure 5.7: Narrow band plots of the six component two-temperature model, with the contributions of the hotter and cooler components plotted separately, of the Cygnus A spectrum for Si xiv Ly α , S xv Ly α , and Fe xxv He α . Only the full model and two CIE component contributions are shown. Model details are provided in section 5.2. The spectra are binned for plotting purposes.

Chapter 6

Conclusion

6.1 Summary

In this thesis, I studied the impact of radio mode AGN feedback on the intracluster medium in galaxy clusters. This thesis focused on the temperature and velocity structures of the intracluster medium in three galaxy clusters: Perseus, Hydra A, and Cygnus A. Spectroscopic X-ray data from XRISM Resolve of each of these clusters was studied and modeled with the fitting program Xspec to extract full pointing measurements or radial profiles of temperature, metal abundance, velocity dispersion, and bulk velocity of the X-ray emitting gas. By piecing together the thermal and kinematic dynamics of the intracluster medium in galaxy clusters, we can learn more about how AGN feedback affects galaxy clusters in the late universe.

In Chapter 3, we used the data from the five XRISM Resolve pointings of the Perseus cluster to establish radial profiles of temperature, metal abundance, velocity dispersion, and bulk velocity up to ~ 250 kpc from the cluster center. We measure a radially-increasing temperature profile, and a radially-decreasing mean abundance profile, which is consistent with typical cool core clusters. We find a radially-declining velocity dispersion profile in the inner ~ 60 kpc, which suggests that the jets and bubbles may be driving turbulence in the core [133]. Beyond 100 kpc, we measure higher velocity dispersions, with a ~ 50 km s $^{-1}$ jump at ~ 7 arcmin likely due to a cold front [133]. Additionally, the inner regions of the cluster are remarkably quiescent, showing velocity dispersions of ~ 175 km s $^{-1}$ or less. The velocity dispersions are interpreted to be due to turbulence. Calculations of heating and cooling in the cluster core indicate that the core may be under-heated, however the large uncertainty in the injection scales indicate that heating and cooling may

be balanced. We further analyzed the data to determine the temperature structure of the Perseus cluster. Flux ratio measurements were consistent with a single temperature gas in collisional ionization equilibrium, and were consistent with the first analysis and Hitomi measurements [24, 58]. However, spectral analysis using multiple temperatures detected a significant cooler (~ 2.3 keV) gas component in the inner ~ 60 kpc of the cluster. This component features a significantly larger velocity dispersion of $\sim 300 - 400$ km s $^{-1}$, implying up to mildly transonic turbulence and a high non-thermal pressure fraction. The interpretation of the cooler component is unclear, however it may represent gas sloshing from a merger, or cooler gas being churned by the jets and bubbles.

In Chapter 4, we used the XRISM Resolve data of the Hydra A cluster to measure temperature, velocity dispersion, and bulk velocity over a $\sim 190 \times 190$ kpc region centered on the cluster. Hydra A features one of the most powerful radio jets along with a massive cavity system throughout the intracluster medium. Measurements of this cluster would help test the relationship between jet power and the dynamics of the intracluster medium. However, we detected a relatively low velocity dispersion of 164^{+10}_{-10} km s $^{-1}$, along with a small velocity offset of -37^{+20}_{-17} km s $^{-1}$ between the gas and the central galaxy. This suggests that the relationship between jet power and the velocity structure of the ICM is not as significant as expected [103]. Additionally, we find that heat due to turbulent dissipation may be insufficient to balance cooling in the inner ~ 93 kpc of the cluster. However, analysis of the outer regions of the cluster are needed to fully understand the dynamics of the intracluster medium in Hydra A.

In Chapter 5, we used the XRISM Resolve data of the Cygnus A cluster to measure temperature, velocity dispersion, and bulk velocity over a $\sim 195 \times 195$ kpc region centered on the cluster. The powerful radio jet, large radio lobes and X-ray cavities, and the cocoon shock suggest that Cygnus A presents one of the most extreme atmospheres, with expectations of high velocity dispersions, making it a prime candidate to study how such extreme conditions can affect the intracluster medium. We measure a relatively high velocity dispersion of 272^{+14}_{-13} km s $^{-1}$, along with a bulk velocity of 101 ± 26 km s $^{-1}$, implying that the intracluster medium is redshifted relative to the central galaxy. Calculations of the dynamics place upper limits on the 3D Mach number ($\lesssim 0.40 \pm 0.02$), and a non-thermal pressure fraction ($\lesssim 8.3 \pm 0.8\%$) consistent with other objects. Due to the nature of the cluster, the observed velocity dispersion and bulk velocity is likely a mix of turbulence and motion of the cocoon shock [76]. A second temperature component with moderate statistical significance was observed. This component features a cooler temperature ($2.06^{+0.43}_{-0.20}$ keV) that is potentially blueshifted (-311 ± 118 km s $^{-1}$) with respect to the central galaxy. This component suggests a large velocity dispersion of 333^{+127}_{-129} km s $^{-1}$. Closer inspection of the Si xiv Ly α , S xv Ly α , and Fe xxv He α emission lines reveal that the two-temperature

model properly fit asymmetrical broad features in these lines. While the lower energy emission lines and statistics suggest that this component is significant, the large statistical uncertainties in the parameters suggest otherwise.

6.2 Concluding Remarks

The Perseus and Hydra A clusters report relatively similar velocity dispersions within the cluster cores, despite the vast differences in jet power. Similarly, the analyses suggest that heating due to turbulent dissipation is insufficient to balance cooling within the same regions. While the Cygnus A cluster reports a higher velocity dispersion, it likely reflects both turbulent motions and motion from the cocoon shock, therefore the turbulent velocity is lower than the velocity dispersion. Although these analyses are subject to uncertainties in the injection scales, it suggests that turbulence alone may not be a sufficient source of heating to offset radiative cooling losses in galaxy clusters. While this is subject to the unknowns of the injection scales, it indicates that the precise dynamics of heating in galaxy clusters is still unclear. As XRISM observes more galaxy clusters, not only should turbulence and the injection scales be investigated, but other potential sources of heating (e.g. sound waves, shock heating, cosmic rays) should be explored as well, as it is clear that the atmospheres of galaxy clusters are far more dynamically complex.

Evidence for a second temperature component is found in both the Perseus and Cygnus A clusters. Both components report a relatively cooler temperature ($\lesssim 2.5$ keV), as well as a high ($\sim 300 - 400$ km s $^{-1}$) velocity dispersion larger than their hotter component counterparts. This component is not detected in Hydra A, which may be due to insufficient signal as it is the shortest observation of the three objects. While the significance of the second component is uncertain in Cygnus A, the existence of the second component in Perseus is highly likely. The multiple temperature analysis of the Perseus cluster shows that the second component's significance, along with its cooler temperature and high velocity dispersion, is robust against systematic effects. This suggests a discovery of a cooler and broader gas component in Perseus that potentially represents sloshing gas from a merger or gas being highly disturbed due to the jets and bubbles. While it is unknown what the true dynamics of the cooler component are, its detection provides a new avenue of investigation into the temperature and velocity structure, and potentially turbulence and heating, of the ICM. Future studies of galaxy clusters with XRISM, including the three galaxy clusters analyzed in this thesis, should focus on multiple temperature modeling, especially on constraining the velocity dispersion and bulk velocity, to develop our understanding of these new second temperature components.

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APPENDICES

Appendix A

XRISM Data Reduction & Analysis Guide

This appendix includes information on software installation for XRISM analysis, a shortened version of the guideline for data reduction of XRISM data outlined in the XRISM Quick-Start Guide v2.1 [122], additional information for [ARF](#) generation and SSM techniques, velocity correction, and modifications to the empirical NXB model provided by the XRISM team.

A.1 Introduction

This guide is a rewritten version of the XRISM quick start guide and other instruction manuals provided in the XRISM Confluence, designed to have compiled all the steps needed to get started with your XRISM data in one single document. Non-public links and decryption codes are not included in this document.

In the XRISM PV Target Discussion Confluence, there is a channel called “(Reference) from Science Operations Team”. From here, you have all the technical instructions for downloading software as well as the quick start guide and the decryption key for the encrypted files we will be downloading.

A.2 Dependencies

Important Note: This section outlines installation instructions for older versions of XRISM software and calibration database files. Newer versions of HEASoft (v6.35 and later) have all the XRISM software tasks that are up-to-date, and CALDB now provides complete public versions of calibration database files for XRISM. This section is included purely for documentation of older version installation.

A.2.1 XRISM Software

The first of three things you need to install is the XRISM software. As of writing this subsection, the latest version is XRISM Build 7.

In the reference channel in Confluence, go to ‘XRISM SDC Tools Pre-Launch Builds’. Scroll down to the relevant build, and access the ReadMe file (`README_XRISM_Build7.txt`). Download the encrypted tar file from the link given in the text file. Using the decryption program (the same one used to decrypt the data), decrypt this file and then relocate the decrypted version to where you would like (I choose to put it in `~/Software` where all my other software folders are kept). In this directory, unpack the file with the command

```
tar -zxvf XRISM_150ct2023_Build7_src.tgz
```

This will create a directory for the XRISM software.

Next, go into the build directory and configure & make the software with the following commands: `cd XRISM_150ct2023_Build7/BUILD_DIR`

```
./configure
```

```
./hmake all
```

```
./hmake install
```

Each command will spit out a lot of stuff into the terminal and take some time. It should finish without any issues. The software is now installed.

Now, we will configure our environment to be able to initialize and call this software anywhere in the computer. Go back to the XRISM software top level directory (`.../XRISM_150ct2023_Build7`) and look for a folder that has either the string ‘i686’ or ‘x86_64’. This is what calls the machine architecture (for example, in my computer the folder is called `x86_64-pc-linux-gnu-libc2.35`). Go to that folder in your terminal. Run the command `echo $PWD`. Open your environment file (e.g. `.bashrc` using `gedit` with `gedit ~/.bashrc`), and add the following lines to it:

```
HEADAS="what you got from echo $PWD"
```

```
export HEADAS
alias heainit=". $HEADAS/headas-init.sh"
```

These lines will now allow you to call the command `heainit` in any directory to initialize the software. Make sure you have restarted the terminal after making these changes.

Important Note: If you have installed and setup any other HEASoft software, they also call the variable `HEADAS` in the environment file (`.bashrc`). To avoid the setup lines in `.bashrc` overwriting each other when you boot up the terminal, comment out the setup lines of whichever software you do not plan to use at that time.

A.2.2 CalDB

The second thing you need is CalDB, found in the HEASARC website. This is the calibration database.

To begin, in your software directory (`~/Software`) add a folder where you will put the CalDB stuff. I chose `~/Software/caldb`. Go into that directory, and run the command `wget https://heasarc.gsfc.nasa.gov/FTP/caldb/software/tools/...caldb_setup_files.tar.Z`

Now unpack the downloaded tar file with `tar -zxvf caldb_setup_files.tar.Z`. Go into the tools directory with `cd /software/tools`. In there you should find 4 files: `alias_config.fits`, `caldb.config`, `caldbinit.csh`, `caldbinit.sh`. Depending on what your terminal is based on, open either `caldbinit.csh` (for unix C-shell) or `caldbinit.sh` (for unix Bourne shell). Uncomment lines 12-14, and change line 12 to the appropriate directory (the directory you created in `/Software` for `caldb`).

Next, we need to download the Hitomi and XRISM calibration data. Access the instructions at `README_XRISM_CalDB_8_Release_Notes.txt`. In the top-level directory (you can now easily access this directory with `cd $CALDB` after restarting the terminal), download and unpack the Hitomi calibration data following the instructions. It is important that you **download the Hitomi data first** (the XRISM calibration data depends on it). Next, download, decrypt, and unpack the XRISM calibration data following those instructions.

Recall the two config files in `.../Software/caldb/software/tools`: `alias_config.fits`, `caldb.config`. These are old and we will be replacing them with 2 newer versions for XRISM. **You have to use the new ones or the data processing will fail.** You can access the newer versions by downloading them from the links provided in the CalDB 8 release notes. Make sure to delete the old ones and put the new ones in `/software/tools`. Finally, we open the environment file (`.bashrc`) and add the following lines:

```
export CALDB="your caldb directory path"
export CALDBCONFIG="$CALDB/software/tools/caldb.config"
export CALDBALIAS="$CALDB/software/tools/alias_config.fits"
alias caldbinit=". $CALDB/software/tools/caldbinit.sh"
```

You can now call the command `caldbinit` in any directory to initialize the calibration data that the other softwares and functions will depend on.

A.2.3 XSelect Mission Database

The last thing you need is an XSelect mission database file. In the science reference page in Confluence, go to Data Analysis and Reduction Tips, and then to Things to Watch Out for in Pipeline-Processed Data. Here, under XSelect, find the file called `xselect.mdb.xrism`. Download it, and put it in a directory you can call later (I put it in the top level directory of the XRISM software, but you can put it anywhere where it won't be tampered with). Open your environment file once again (`.bashrc`), and add the following line

```
export XSELECT_MDB="the directory you put the file/xselect.mdb.xrism"
```

Important Note: Like the situation with HEADAS, other HEASoft softwares may use this same variable in `.bashrc`. You will have to comment out the one you don't plan on using at that time just like with HEADAS.

A.3 Data Processing

For this, the latest version of the XRISM quick start guide should be used. We will go through a condensed version of the same steps here (of version 2.1 of the guide) for the Resolve instrument only.

A.3.1 Initial Setup

Start with the directory for the observation. For this example, we will use one of the C0 pointings for Perseus: `.../000154000/`. In this directory, make a new directory called `analysis`. Copy all the decrypted and unpacked files from `.../000154000/resolve/events_c1` and paste them in the `analysis` folder. We will now

quickly do a sanity check regarding the RA, DEC, PA, and exposure from the cleaned event file. Run the command

```
ftlist xa000154000rsl_p0px1000_cl.evt K include="RA_NOM,DEC_NOM,...  
...PA_NOM,EXPOSURE"
```

and record the values for RA_NOM, DEC_NOM, PA_NOM (or add > keywords.txt at the end of the command to auto-output into a file). Verify that the value given for EXPOSURE is around what you expect. If there are multiple sets of values spit out for these headers, they should be the exact same values. Finally, copy the following files and put them in the analysis directory: 000154000/auxil/xa000154000.ehk.gz
000154000/resolve/event_uf/xa000154000rsl_px1000_exp.gti.gz

A.3.2 Resolve Rise-Time Screening

Execute the following command in the analysis directory:

```
ftcopy infile="xa000154000rsl_p0px1000_cl.evt[EVENTS] [(PI>=600) &&  
((((RISE_TIME+0.00075*DERIV_MAX)>46)&&((RISE_TIME+0.00075*DERIV_MAX)<58))  
&&ITYPE<4)|| (ITYPE==4))&&STATUS[4]==b0]" outfile=xa000154000...  
...rsl_p0px1000_cl2.evt copyall=yes clobber=yes history=yes
```

A.3.3 Extract Broadband Images and Establish Source Center Coordinates

Start XSelect, and run the following commands

```
xselect> read events xa000154000rsl_p0px1000_cl2.evt .  
xselect> set image DET  
xselect> filter pha_cutoff 4000 20000  
xselect> extract image  
xselect> save image xa000154000rsl_p0px1000_detimg.fits
```

This creates a 2-10 keV Resolve image in DET coordinates. When running the first command, XSelect may prompt you to reset the mission, if it does type **yes**. Now open this fits file in DS9 and roughly measure the source center in DETX-DETY coordinates. We will refer to these coordinates as RDETX0 and RDETY0. You should expect to find that these values are both 3.5. If they don't appear to be (sometimes DS9 includes multiple coordinate systems, which may or may not all give the same values), a later step will verify what the right values are.

A.3.4 Extract Lightcurves and Spectra

Start a new XSelect session (or type `clear all` if you never stopped the current one), and read in the cleaned Resolve event file

```
xselect> read events xa000154000rsl_p0px1000_cl2.evt .
```

Then run the following commands to extract a light curve

```
xselect> set image det
```

```
xselect> filter pha_cutoff 4000 20000
```

```
xselect> set binsize 128.0
```

```
xselect> extract curve exposure=0.8
```

```
xselect> save curve xa000154000rsl_allpix_b128_lc.fits
```

If XSelect spits out an error at `extract curve exposure=0.8`, just keep lowering the exposure value until it works. In this example, I had to lower it to 0.2.

Now we will extract a Resolve spectrum from the full array with the following commands

```
xselect> filter column "PIXEL=0:11,13:35"
```

```
xselect> filter GRADE "0:0"
```

```
xselect> extract spectrum
```

```
xselect> save spectrum xa000154000rsl_allpix_Hp_src.pi
```

You can modify the filter column command to only include any subset of pixels.

A.3.5 Make RMFs

Warning: There is currently a bug with `rslmkrmf` with the `regionfile` parameter. If you plan on using any set of pixels that is not the default (i.e. all except pixel 12) use the `pixlist` parameter instead and set `regionfile=NONE`. See the `rslmkrmf` help page for information on how to use the `pixlist` parameter.

Make a large Resolve RMF with the commands

```
punlearn rslmkrmf
```

and

```
rslmkrmf infile=xa000154000rsl_p0px1000_cl2.evt
```

```
outfileroot=name_obs1_60k_60k_Hp_allpix_L regmode=DET whichrmf=L
```

```
resolist=0 regionfile=ALLPIX emin=0.0 dein=0.5 nchanin=60000 useingrd=no
```

```
eminout=0.0 deout=0.5 nchanout=60000
```

Change the name part of `outfileroot` to the name of the object you are studying.

We make a small Resolve RMF with

```
punlearn rslmkrmf
```

RMF Size	Gaussian Core	Exponential Tail	Si K α Instrumental Line	Escape Peaks	Electron Loss Continuum
S	Y	N	N	N	N
M	Y	Y	N	N	N
L	Y	Y	Y	Y	N
X	Y	Y	Y	Y	Y

Table A.1: What effects are included in the chosen RMF size.

and

```
rslnkrmf infile=xa000154000rsl_p0px1000_cl2.evt
outfileroot=name_obs1_60k_60k_Hp_allpix_S regmode=DET whichrmf=S
resolist=0 regionfile=ALLPIX
```

Table A.1 describes all the types of effects that are included depending on the size of RMF chosen (with the `whichrmf=` option). The extra-large option (X) is problematic, however, as the file size can be roughly 7 GB large. This can cause problems with other software like SPEX or XSPEC. When X size RMFs are needed (for analysis using lower energies of the spectra), you must include the command `splitrmf=yes` to allow for RMF splitting which will reduce file size by splitting the ELC into its own RMF, and `splitcomb=yes` to make a combined RMF file which is what will be needed for Xspec analysis.

A.3.6 ARFs

Exposure Map

First, we need an exposure map. To do this, run

```
punlearn xaexpmap
and
xaexpmap ehkfile=xa000154000.ehk.gz
gtifile=xa000154000rsl_p0px1000_cl2.evt.gz instrume=RESOLVE
badimgfile=NONE pixgtifile=xa000154000rsl_px1000_exp.gti.gz
outfile=xa000154000rsl_p0px1000.expo outmaptype=EXPOSURE delta=20.0
numphi=1 stopsys=SKY instmap=CALDB qefile=CALDB contamifile=CALDB
vigfile=CALDB obffile=CALDB fwfile=CALDB gvfile=CALDB maskcalsrc=yes
fwtype=FILE specmode=MONO specfile=spec.fits specform=FITS
evperchan=DEFAULT abund=1 cols=0 covfac=1 clobber=yes chatter=1
logfile=make_expo_xa000154000rsl_p0px1000.log
```

Note that the files in the second command are all written in gzipped format. If you have unzipped these files just edit the extensions as appropriate.

Coordinate Check

Now we verify what the appropriate coordinates are for RDET XO and RDET YO. Now run the following two commands

```
punlearn coordpnt
```

and

```
coordpnt input="RDET XO,RDET YO" outfile=NONE telescop=XRISM  
instrume=RESOLVE teldeffile=CALDB startsys=DET stopsys=RADEC ra=RA_NOM  
dec=DEC_NOM roll=PA_NOM ranom=RA_NOM decnom=DEC_NOM clobber=yes  
for the values you found for RDET XO and RDET YO, as well as 3.5 for both of these values.  
Note that you will have to replace the values for RA_NOM, DEC_NOM, PA_NOM that you  
found earlier.
```

Verify that the second command spits out an output RA & DEC within 10" or so of what you expect them to be. Whichever values you have for RDET XO and RDET YO that achieve this are the correct ones.

Generating ARF

We will now generate a point source ARF.

Before making the ARFs, in order to avoid version conflicts, delete the parameter files for `xaarfgen` and `xaxmaarfgen` in your local `pfiles/` directory (in `/home/user/pfiles`) labelled `xaarfgen.par` & `xaxmaarfgen.par`.

Now run the following two commands

```
punlearn xaarfgen
```

and

```
xaarfgen xrtevtfile=raytrace_xa000154000rsl_p0px1000_ptsrc.fits  
source_ra=rslsrc_ra source_dec=rslsrc_dec telescop=XRISM instrume=RESOLVE  
emapfile=xa000154000rsl_p0px1000.expo regmode=DET  
regionfile=region_RSL_det.reg sourcetype=POINT  
rmffile=targetname_obs1_60k_60k_Hp_allpix_L.rmfile erange="0.3 18.0 0 0"  
outfile=xa000154000rsl_p0px1000_ptsrc.arf numphoton=300000 minphoton=100  
teldeffile=CALDB qefile=CALDB contamifile=CALDB obffile=CALDB fwfile=CALDB  
gatevalvefile=CALDB onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB
```

```
obstructfile=CALDB frontreffile=CALDB backreffile=CALDB pcolreffile=CALDB  
scatterfile=CALDB mode=h clobber=yes seed=7 imgfile=NONE
```

Be careful to choose the appropriate RMF file (the one you chose to generate). The RMF and ARF energy grids will be matched when generating the ARF, so a mismatched grid will cause errors. You do NOT have to re-generate an ARF if you generated one with a certain size RMF and want to use a different size RMF in analysis as long as the only difference is the RMF size (e.g. L vs X), but if you changed any other parameter in `rslmkrmf` (e.g. `pixlist`, `nchanout`, ...) then you will have to re-generate the ARF.

When running `xaarfgen`, if there is a warning or error that there is an insufficient number of raytracing photons, it does not necessarily mean that you should increase the number of input photons. It may mean that the raytracing photons are missing the region on the detector, which could be due to an error in coordinates and/or the region file. These latter items should be checked first, before increasing the number of input photons.

If you are using a different subset of pixels (e.g. removing pixel 27), you will have to use a different region file appropriate to that subset.

A.4 Pixel Sub-Arrays

This section describes how to generate the spectrum, RMFs, region file, and ARFs for pixel sub-arrays (e.g. removing Pixel 27, or a subarray for different regions of the cluster).

The help files for the tasks used in the generation of RMFs, ARFs, etc... are found in the `xrism` folder in the XRISM build 7 directory (or the respective software). For example, one can find the help file (the file ending in `.html`) for `xaarfgen` at `.../XRISM_150ct2023_Build7/hitomixrism/xrism/mission/tasks`, or `rslmkrmf` at `.../XRISM_150ct2023_Build7/hitomixrism/xrism/resolve/tasks`.

A.4.1 Spectrum & RMF

The spectrum & RMF are actually pretty simple. It just requires changing one or two parameters.

Start a new XSelect session (or type `clear all` if you never stopped the current one), and read in the cleaned Resolve event file

```
xselect> read events xa000154000rsl_p0px1000_c12.evt .
```

Now we will extract a Resolve spectrum from the full array except pixel 27 with the

following commands

```
xselect> filter column "PIXEL=0:11,13:26,28:35"  
xselect> filter GRADE "0:0"  
xselect> extract spectrum  
xselect> save spectrum xa000154000rsl_no27_Hp_src.pi
```

Now we will extract a Resolve spectrum from a sub-array (this example: pixels 0, 1, 2, 4, and 11) with the following commands

```
xselect> filter column "PIXEL=0:2,4:4,11:11"  
xselect> filter GRADE "0:0"  
xselect> extract spectrum  
xselect> save spectrum xa000154000rsl_afewpixels_Hp_src.pi
```

Take notice to the command formatting when choosing 1 pixel at a time.

Make a large Resolve RMF for the full array except pixel 27 with the commands

```
punlearn rslmkrmf
```

and

```
rslmkrmf infile=xa000154000rsl_p0px1000_cl2.evt  
outfileroot=name_obs1_60k_60k_Hp_no27_L regmode=DET whichrmf=L resolist=0  
regionfile=NONE pixlist=0-26,28-35 emin=0.0 dein=0.5 nchanin=60000  
useingrd=no eminout=0.0 deout=0.5 nchanout=60000
```

or for a sub-array (region 0 example) with

```
rslmkrmf infile=xa000154000rsl_p0px1000_cl2.evt  
outfileroot=name_obs1_60k_60k_Hp_reg0_L regmode=DET whichrmf=L resolist=0  
regionfile=NONE pixlist=0,2,10,15,17-18,20,25,33,35 emin=0.0 dein=0.5  
nchanin=60000 useingrd=no eminout=0.0 deout=0.5 nchanout=60000
```

Change the name part of outfileroot to the name of the object you are studying, and the allpix part to what the appropriate sub-array/region is. Notice that the difference here is that we changed regionfile=ALLPIX to reigonfile=NONE and added the pixlist parameter.

A.4.2 Region File

Region files are created using DS9. Since the XRISM pixels are all effectively boxes, we can use the physical coordinate system to determine the pixels we want to use. The DS9 box command is used as "box x y width height" and we can specify the coordinate system of choice. A list of DS9 regions for each pixel in DET coordinates are provided below

```
box(4,3,1,1,0) # pixel 0
box(6,3,1,1,0) # pixel 1
box(5,3,1,1,0) # pixel 2
box(6,2,1,1,0) # pixel 3
box(5,2,1,1,0) # pixel 4
box(6,1,1,1,0) # pixel 5
box(5,1,1,1,0) # pixel 6
box(4,2,1,1,0) # pixel 7
box(4,1,1,1,0) # pixel 8
box(1,3,1,1,0) # pixel 9
box(2,3,1,1,0) # pixel 10
box(1,2,1,1,0) # pixel 11
box(2,2,1,1,0) # pixel 13
box(2,1,1,1,0) # pixel 14
box(3,2,1,1,0) # pixel 15
box(3,1,1,1,0) # pixel 16
box(3,3,1,1,0) # pixel 17
box(3,4,1,1,0) # pixel 18
box(1,4,1,1,0) # pixel 19
box(2,4,1,1,0) # pixel 20
box(1,5,1,1,0) # pixel 21
box(2,5,1,1,0) # pixel 22
box(1,6,1,1,0) # pixel 23
box(2,6,1,1,0) # pixel 24
box(3,5,1,1,0) # pixel 25
box(3,6,1,1,0) # pixel 26
box(6,4,1,1,0) # pixel 27
box(5,4,1,1,0) # pixel 28
box(6,5,1,1,0) # pixel 29
box(6,6,1,1,0) # pixel 30
box(5,5,1,1,0) # pixel 31
box(5,6,1,1,0) # pixel 32
box(4,5,1,1,0) # pixel 33
box(4,6,1,1,0) # pixel 34
box(4,4,1,1,0) # pixel 35
```

Keep in mind that the organization of the pixels is not regular.

A.4.3 ARFs

When generating the ARF with a different region file, all one needs to do is just change the `regionfile=` parameter to the region file you created in the previous section. The RMF you will use to generate the ARF needs to match the pixels chosen.

A.5 Other things

A.5.1 Barycentric correction

To apply a barycentric correction to your measured bulk velocity, you need two files: the event file (e.g. `xa000154000rsl_p0px1000_cl.evt`) and the orbit file. The orbit file is found in the `xa000154000/auxil` folder, and is found as `xa000154000.orb.gz`. To calculate the barycentric correction, run the following command in the analysis directory:

```
barycen infile="xa000154000rsl_p0px1000_cl.evt" outfile="jnk"
orbfile="../auxil/xa000154000.orb.gz" orbext="ORBIT" ra=49.95068
dec=41.51172 refframe="FK5" debug=yes > orb.txt
```

where the `ra` and `dec` parameters are the values you found when searching for the nominal RA and DEC keywords.

This command will output a log file called `barycen.log`, open this file (warning: it is long!). It will list a table of values for each measured time point in the event file. Scroll all the way to the bottom and you will find these values for the start and end times of the observation. The keyword `ERADVEL` is the barycentric correction, and the correction works as $v_{\text{corrected}} = v_{\text{bulk}} + \text{ERADVEL}$, even if `ERADVEL` is a negative value. Depending on your analysis you may need a sophisticated method, but the difference over the entire observation is at most $0.5\text{--}1\text{ km s}^{-1}$, so just taking the average of the start and end velocities should be sufficient. This command will also output a fits file called `jnk.fits` – you don’t need it.

A.5.2 Spectrum re-binning

Depending on your science objective, it may be better or even necessary to re-bin your spectra to ensure at least a minimum of 1 count or more per bin.

The HEASoft routine `ftgrouppha` is what you will use for this. The documentation for it is actually really simple, with a few binning options, but here’s an example. If I wanted

to ensure a minimum of 1 count per bin, I would run the command:

```
ftgrouppha infile=xa000154000rsl_allpix_Hp_src.pi  
outfile=xa000154000rsl_allpix_Hp_src_minbin.pi grouptype=min groupscale=1
```

A.5.3 NXB Modification

If you are using a sub-array in your analysis, the empirical NXB model must be changed to avoid over-accounting for the NXB. After you fit the NXB model for the full pointing array (all pixels except 12 & 27), you will need to modify the first parameter of the model which dictates the overall ‘strength’ of the NXB. In the `.xcm` file of the output model from the official fit instructions, multiply the first parameter’s fit value by the ratio of pixels in the sub-array to the total number of pixels (e.g. if the sub-array uses only 10 out of the 34 pixels, multiply it by 10/34). If the sub-array is small enough the parameter value will be below the 1σ lower bounds set by the XRISM team, to remedy this simply modify the ‘low’ and ‘min’ of the parameter to a range that includes the new value.

Note: this technique only works properly when you are freezing the NXB model in the fit of your data.

A.6 CIAO & Chandra

A.6.1 Making source images for ARFs using Chandra observations

Download the data from ChaSeR (<https://cda.harvard.edu/chaser/>).

Reprocess the data with CIAO using the `chandra_repro` task.

If you need to cut out sub-regions from the reprocessed image (e.g. to use in ARF generation), use the CIAO `dmcopy` task with a region file (in CIAO format) to make a cropped version. Refer to <https://cxc.cfa.harvard.edu/ciao/threads/regions/> for more information.

A.6.2 Exposure Corrected Mosaic

To make an exposure corrected combined mosaic from multiple observations, refer to https://cxc.cfa.harvard.edu/ciao/threads/reproject_image/index.html

NOTE: Products generated from this are not suitable for most CIAO tools or spectral fitting (see warnings in that thread). The best use case for this XRISM-wise is to make

a larger or more defined map from multiple Chandra observations for a source image for ARF generation. It also makes pretty pictures for papers.