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Analyzing Chandra X-ray Observations of the Infalling Galaxy Group NGC 4839 in the Nearby Coma Cluster

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by

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Abstract

Cosmological simulations indicate that present day galaxy clusters predominantly grow in mass through the accretion of smaller galaxy groups. Ram pressure stripping acts to strip gas away from these groups, forming large, cold tails. I will use new Chandra X-ray observations of the infalling galaxy group NGC 4839 in the nearby Coma cluster, the lowest redshift example of a group falling into a massive cluster that has a stripped gas tail. I will investigate the heating and stripping away of NGC 4839's gas as it falls into the Coma cluster.

Background

Galaxy Clusters

At the beginning of time, all matter was distributed amongst the universe in a mostly uniform great cloud. Over the lifetime of the universe, gravitational forces have clumped slightly denser regions of matter together into larger and larger structures such as stars and galaxies. In the current day, the matter of the universe has condensed into weblike superstructures called galaxy clusters. Galaxy clusters can be likened to a cupcake in composition: the galaxies we observe serve as pretty sprinkles upon a “frosting” containing around 4 times as much mass known as the Intracluster Medium (or

ICM) with dark matter supplying the bulk of the mass (over 80%) to act as the cake. These galaxy clusters are the largest and most massive gravitationally bound structures in the universe; on the order of 10^{14}-10^{15} times the mass of the Sun and spanning up to 10 megaparsecs in diameter. But gravity still continues to pull these objects close to each other. When one galaxy group is absorbed into another, it “falls” into the greater mass, moving at great speeds that strip away gasses and other matter from the edges of the cluster to form a cosmic tail, much like a comet does within our own solar system. NGC 4839 is one such galaxy group. It is falling into the much larger Coma Cluster, which makes this the lowest redshift (z = .023) example of such an event. Incidentally, the Coma Cluster was the object used by Fritz Zwicky to prove the existence of dark matter. As we can see in Figure 1, NGC 4839 is clearly exhibiting the comet-like characteristics that are of such interest to X-ray astronomers, streaming large amounts of gas and dust behind it as it plummets.

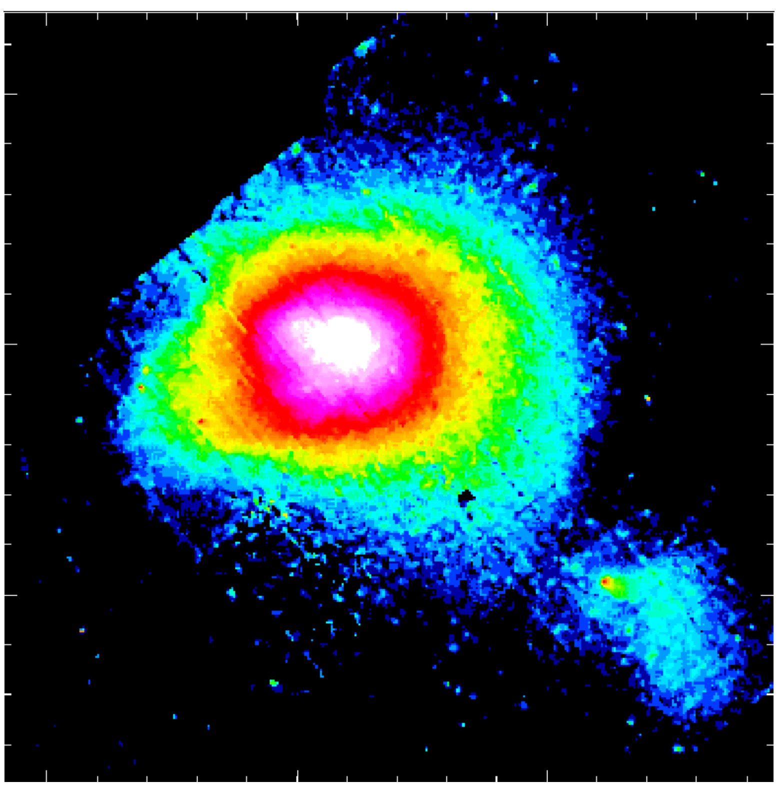

Figure 1: NGC 4839 (bottom right) as it falls into the Coma Cluster (center) *Image by D. M. Neumann, D. H. Lumb, G. W. Pratt, and U. G. Briel*

X-ray Astronomy and Observation

X-rays are a form of electromagnetic radiation, or light, that are highly energised. Because they are so energised, they are relatively rare in the universe when compared to other forms of light. X-rays are produced in areas of high gravitational or magnetic upheaval (basically high energy areas) such as galactic centers, where supermassive black holes reside. This is the reason why X-rays are studied by astronomers; they can provide information on some of the most turbulent areas of the universe. One of the best sources of a particular kind of X-ray, Bremsstrahlung X-rays (figure 2), is the ICM of a galaxy cluster.

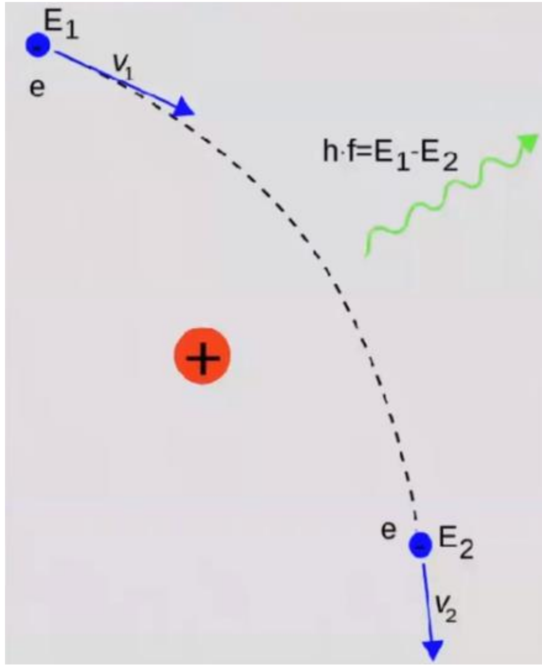

Figure 2: How Bremsstrahlung X-rays are formed

Since ICM's tend to be composed of very superheated yet sparsely distributed plasma (anywhere between 10 million-100 million K and 10^{-4} particles/m^3) they emit Bremsstrahlung X-rays by deflecting super energetic electrons around a positive ion as shown in figure 2. This deflection causes the electron to lose some energy that is emitted from it as an X-ray photon. This energy loss causes the electron to slow down, or “brake”, causing this type of X-ray to get its name, as Bremsstrahlung is German for “braking radiation”. These X-rays emitted from the ICM make the gasses within it much more visible in that spectrum than in optical, where the galaxies dominate (hence the sprinkles in the cupcake analogy). This difference is shown in figure 3.

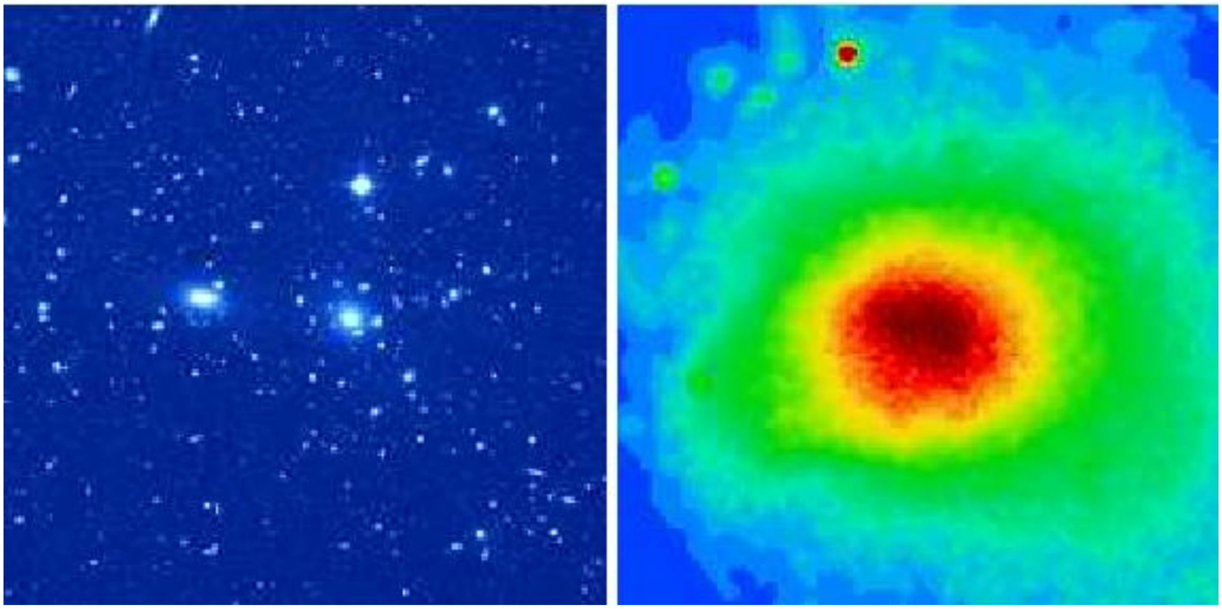

Figure 3: The Coma Cluster as viewed by optical light waves (left) vs X-ray (right) *Image from Astrophysics and Cosmology (2000), by Juan Garcia-Bellido*

The Chandra X-ray Observatory

The Chandra X-ray Observatory (figure 4), launched in July of 1999 and currently orbiting 139,000 km above the Earth, is one of the Great Observatories used by NASA. It is the preemptive source of the X-ray related data used by astronomers to examine the deeper reaches and structure of the universe and also provided the X-ray viewing of the Coma cluster in figure 3. Chandra's use is based on a proposal system where astronomers submit their ideas for how the observatory's observing time should be spent. Typically, proposals have around a year-long wait period and are rejected at a rate of around 5 rejections to every 1 success. This is because Chandra's time is incredibly valuable, and many days at a time must be spent observing one spot in order to collect enough photons to be useful. This issue is compounded by cooling issues in Chandra’s equipment causing the observatory to occasionally need to take breaks after long observations. Also, part of Chandra’s orbit passes through a Van Allen belt within Earth’s magnetosphere, interfering with onboard electronics and effectively making that segment of the orbit a dead zone for observations.

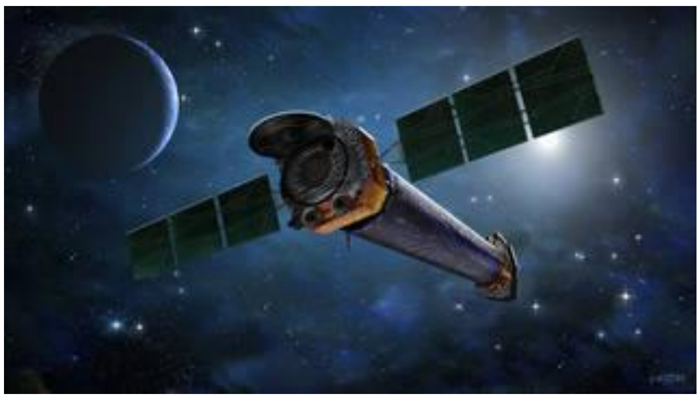

Figure 4: The Chandra X-ray Observatory, *courtesy of NASA.gov*

Chandra uses the ACIS, or Advanced CCD Imaging Spectrometer, to collect data on distant objects and create detailed images or measure spectra. This camera system, housed at the end of a 9 meter-long optical bench, was specifically designed to observe celestial objects such as galaxy clusters or black holes. This has contributed to a great leap in studies for many exciting areas, not just for galaxy clusters.The data used in this report was gathered in 8 segments totalling a combined 231.71 kiloseconds (2.68 days) of observation time to observe and create spectra for NGC 4839.

Method

Motivation

The majority of the data used for this research was gathered over the year of 2020, with one previous observation occurring in late 2010, (figure 5) to examine the properties of the ICM around NGC 4839. Astronomers hope to glean new knowledge on the specifics of what happens when two galaxy groups collide. Since galaxy clusters are already the largest gravitationally bound structures in the universe, they can only increase in mass by this kind of collision, known as Hierarchical Clustering. As it is falling into the Coma Cluster, NGC 4839 is a very convenient candidate for study.

Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name
1	801025	12887	ACIS-I	NONE	45.0	43.44	NGC4839	Forman
2	801878	22648	ACIS-I	NONE	34.0	32.64	NGC 4839	Walker
3	801878	22649	ACIS-I	NONE	35.0	34.12	NGC 4839	Walker
4	801878	22930	ACIS-I	NONE	38.0	36.84	NGC 4839	Walker
5	801878	23182	ACIS-I	NONE	31.0	30.67	NGC 4839	Walker
6	801878	23361	ACIS-I	NONE	20.5	18.83	NGC 4839	Walker
7	801878	24853	ACIS-I	NONE	28.5	26.72	NGC 4839	Walker
8	801878	24854	ACIS-I	NONE	8.0	7.91	NGC 4839	Walker

RA	Dec	Status	Data Mode	Exp Mode	Avg Cnt Rate	Evt Cnt	Start Date
12 57 24.10	+27 29 47.00	archived	VFAINT	TE	4.61	200340	2010-11-11 01:18:1
12 57 11.32	+27 27 40.14	observed	VFAINT	TE	3.72	121265	2020-03-03 16:44:1
12 57 11.32	+27 27 40.14	observed	VFAINT	TE	3.65	124462	2020-03-04 08:00:5
12 57 00.26	+27 28 00.59	observed	VFAINT	TE	3.82	140665	2020-08-11 02:23:4
12 57 11.32	+27 27 40.14	observed	VFAINT	TE	3.61	110607	2020-03-04 22:27:2
12 57 00.26	+27 28 00.59	observed	VFAINT	TE	3.69	69533	2020-11-02 18:46:0
12 57 00.26	+27 28 00.59	observed	VFAINT	TE	3.70	98978	2020-11-03 16:18:4
12 57 00.26	+27 28 00.59	observed	VFAINT	TE	3.71	29316	2020-11-08 01:38:01

Figure 5: The 8 observations I pulled data from split into two halves for easier reading, *provided by cda.harvard.edu*

With observations on the overall temperature and composition of the galaxy group, scientists are one step closer to understanding a fundamental part of the universe.

CIAO

There are surprisingly many steps and processes to turning raw data received from Chandra into workable numbers to put on a graph. First, you start to work in CIAO, or the Chandra Interface, Analysis, and Observation program. Then, the data from each observation needs to be reprocessed into a more clear and usable state. This is accomplished using Chandra_repro, a routine built into CIAO. There are many different stages to the reprocessing routine. Each stage works differently to fix or adjust the observatory data into the final product. First you start with the event files, which contain all the raw, unmodified data in a table. This data is compartmentalized into different sections to form: an image, spectra, lightcurves, sourcelists, or whatever else you might need the data for. Then all of the data is calibrated to account for many different factors. The Instrument Map, Exposure Map, and Bad Pixel file adjust the data for specific errors in the ACIS detector, such as over or underperforming areas or individual pixels within the camera. Since Chandra is in space, it is much easier to calibrate slightly off data in this manner than to send a team out to fix the observatory. After all of this calibration, your data is reprocessed, and is ready to be used.

With the reprocessed data, I used a command called merge_obs to combine each of the 8 observations into a single, exposure-corrected image (figure 6).

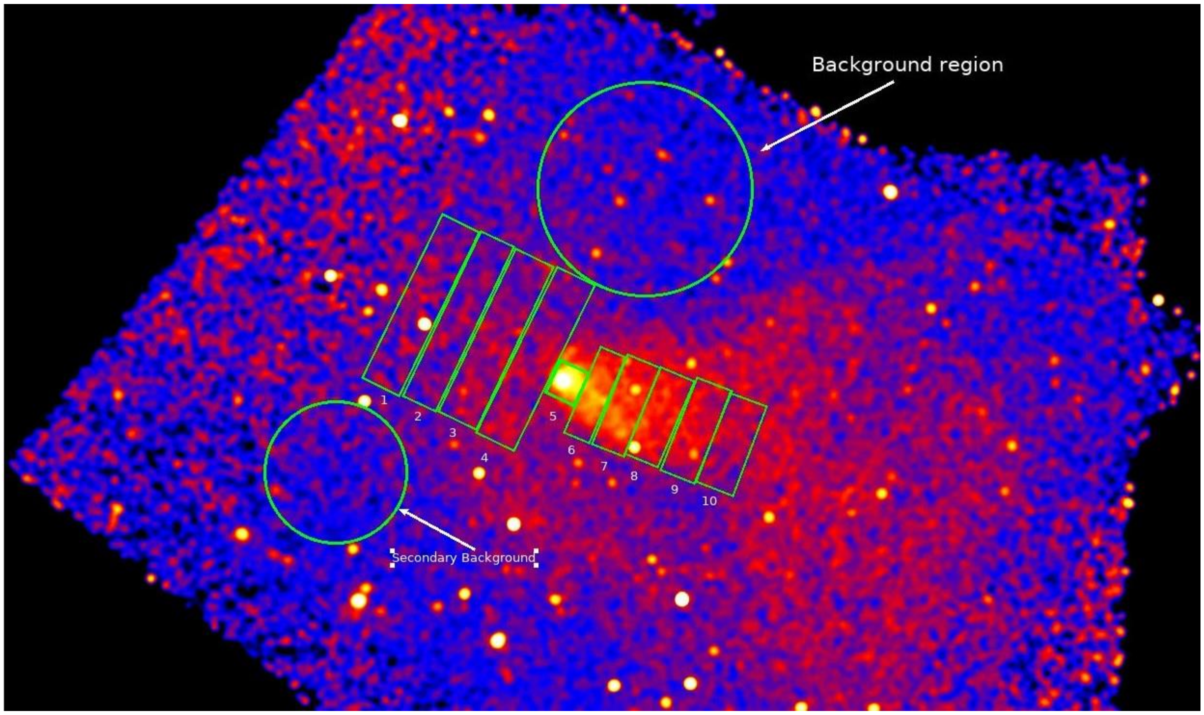

Figure 6: Combined image and regions using DS9

Using a tool called DS9 (named for the Star Trek show), I created regions that marked out a set of coordinates for the other programs to work in. DS9 is also helpful for visualization of data, as it can show images from reprocessed Chandra data that the user can then tailor to suit their needs, like what was done in figure 6. For the purposes of the research, I started with a square region around the heart of NGC 4839 and trailed 5 rectangular regions behind it to observe the gas, as well as 4 larger rectangular regions in front of NGC 4839. I also created two large, circular regions above and below the galaxy group to serve as background regions. Background is required to act as a baseline for spectral analysis. These regions can be seen bordered in green in figure 6. After removing the parts of the regions that contained the bright point sources (most likely the centers of other galaxies in the foreground and background), I was ready to extract spectra from each region.

Specextract and Combine_spectra

I extracted spectra from each of the 8 observations and each of the 10 regions using the specextract command. Specextract creates many different files such as: the Pulse Height Amplitude file (PHA) to adjust for contamination data, the Pulse Invariant (PI) file to mask the constant background noise of Chandra's machinery, the Ancillary Response File (ARF) fits to Chandra's sensitivity curve, and the Redistribution Matrix File (RMF) which maps channel to energy. After extracting the spectra of each observation, I used combine_spectra to layer the spectra of all 8 observations on top of each other, creating a single spectrum for each region. Now that I had combined all 80 spectral files into one file for each region, I was ready to pull out the useful spectral data on NGC 4839.

Xspec

Xspec is a program that interprets the reprocessed spectral data into useful information such as: temperature, hydrogen abundance, or redshift, and then outputs this information into convenient graphs and charts for easy understanding (figure 7).

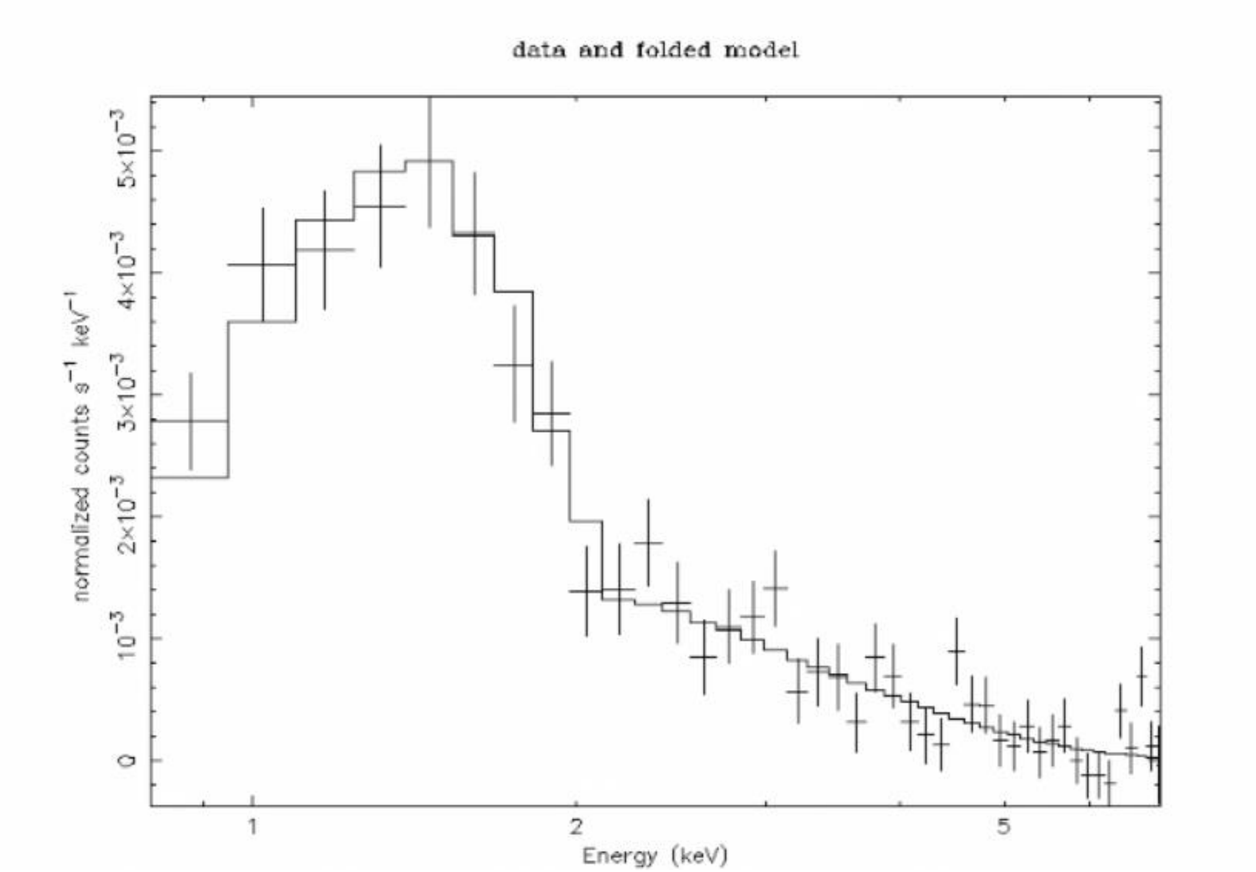

Figure 7: An Xspec best fit graph showing energy counts of region 5

It is helpful to independently look up certain characteristics elsewhere so that you may "freeze" them in. That way, Xspec will be able to produce the most accurate results for the data points you are looking for. In my case, I froze the values of Redshift and Abundance at 0.023 and 0.3 $Z_\odot$, respectively. Once you have your spectral data for a desired region, you feed the appropriate files into Xspec, and you receive graphs and charts of data necessary for interpretation. In my research, once a point source was removed from the region, Region 1 did not have a sufficient number of counts to provide usable data, and thus was cut from the remainder of the project.

Results

Once I had all of my usable data from Xspec, I put it into a graph (figure 8). The hottest region on the graph is region 3. This is evidence that NGC 4839 may be falling at a high enough velocity to have developed a shock front. A shock front can only be generated if the body of mass is travelling faster than the speed of sound of the medium it is travelling in, which in this case would be on the order of 10^3 kilometers per second for the Coma Cluster. As can be seen in figure 9, a shock front will generate high temperatures due to the compression of gas between the infalling object and the galaxy cluster. From the hottest region to the coldest, we now arrive at region 5, which we remember from figure 6 is the heart of NGC 4839. The possible explanation for why this region is so cold is due to the size of the galaxy group. Galaxy groups and clusters generally follow a rule that temperature is higher with increased mass. Since the Coma Cluster is a full order of magnitude more massive than NGC 4839, it makes sense the smaller galaxy group would be the coldest point on the graph. This also explains the warmer tail that can be seen from regions 6-10, the gasses stripped away from NGC 4839 are mixing with the warmer gasses of the greater Coma Cluster.

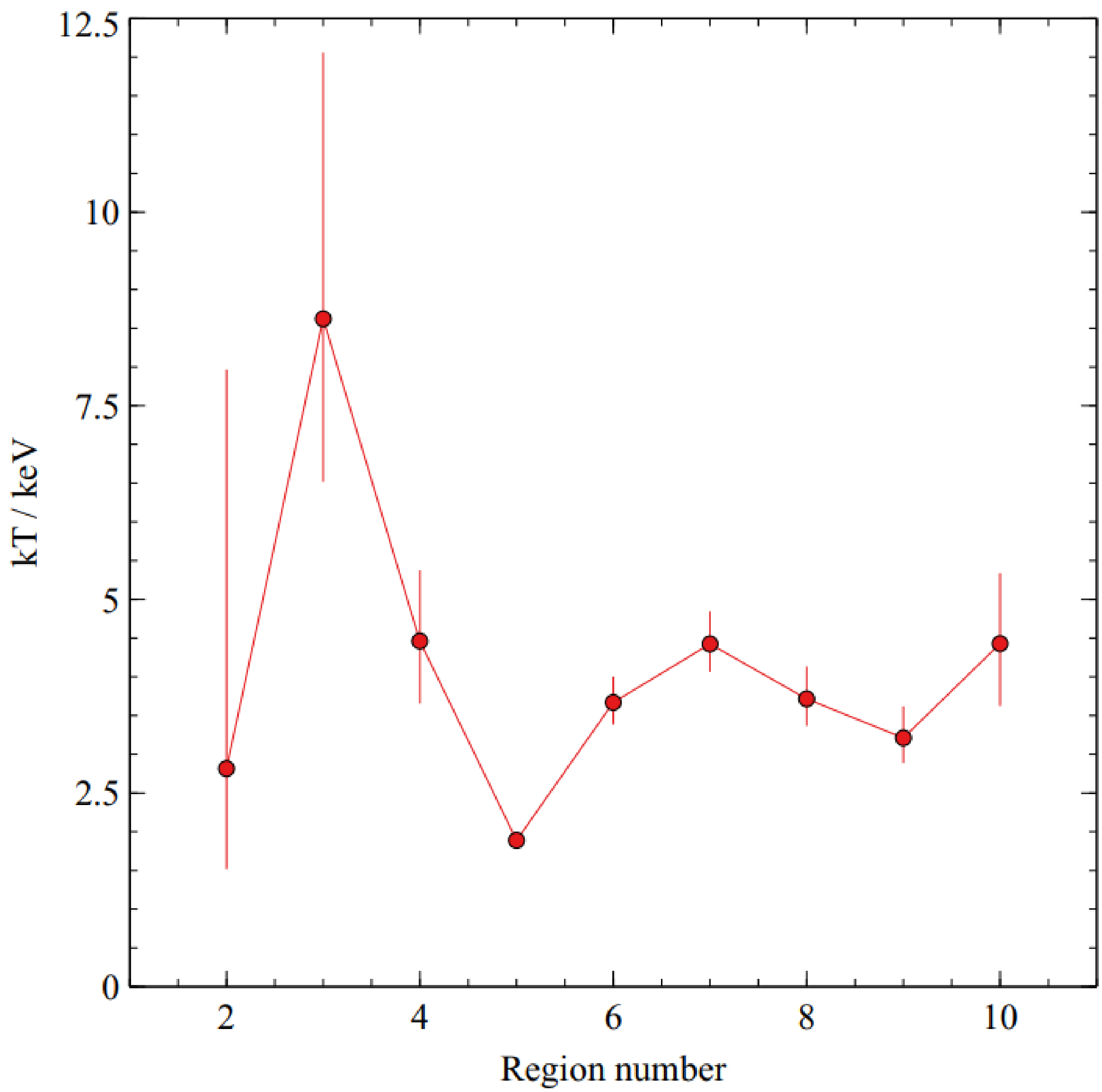

Figure 8: My final results, regions 2-10 and their extracted temperatures.

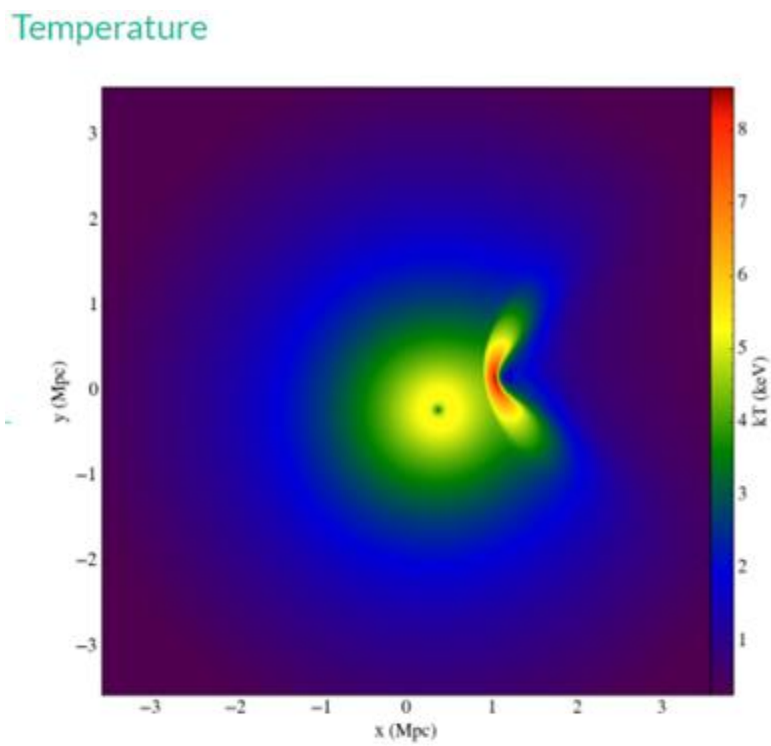

Figure 9: A simulation showing the shock front developed by a fall of similar circumstances to NGC 4839, *provided by gcmc.hub.yt*

Conclusion

To conclude, galaxy clusters are the largest gravitationally bound structures in the universe; composed of dark matter, an Intracluster medium, and the galaxies themselves. The ICMs of these clusters emit x-rays that we observe with the Chandra observatory. I reprocessed raw data from Chandra, extracted spectra, and fed those spectra into Xspec to find the temperatures of several regions along NGC 4839's path into the Coma cluster. Lastly, I found that the galaxy group was moving fast enough to develop a shock front and a warmer tail.

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