

Mass Profile of Abell 2204

An X-ray analysis of Abell 2204 using XMM-Newton data

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Abstract

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The vast majority of the matter in the universe is of an unknown type. This matter is called dark matter by astronomers. The dark matter manifests itself only through gravitational interaction and is otherwise undetectable. The distribution of this matter in can be better understood by studying the mass profile of galaxy clusters. The X-ray emissions of the galaxy cluster Abell 2204 were analyzed using archived data from the XMM-Newton space telescope. We analyze a 40ks observation of Abell 2204 and present a radial temperature and radial mass profile based on hydrostatic equilibrium calculations.

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1 Introduction

Galaxy clusters are the largest gravitationally bound objects in the universe. These clusters exist in sizes ranging from a few galaxies to ten thousand galaxies. The formation of structure in the universe and the distribution of matter in the universe can best be studied by observing galaxy clusters. The gravitational potential which binds the constituent galaxies within a cluster often also binds a vast cloud of hot gas which fills the space between and around the galaxies [1]. The gas has a temperature of millions of degrees Kelvin. This very diffuse gas is a strong source of x-ray emission [1].

The goal of this project is to produce an accurate radial mass profile in order to understand how mass is distributed in a regular galaxy cluster. There are several ways to calculate the mass of a galaxy cluster: velocity dispersion, gravitational lensing, and X-ray data. Regular galaxy clusters contain a large amount of ionized gas (which is responsible for the x-ray emission) that is spherically distributed around the center of the cluster. Studying the x-ray emissions of this thermal plasma will allow for generation of the radial mass profile based on the self-gravitating isothermal sphere model.

The earth's atmosphere blocks most of the indecent x-rays therefore space based observatories are required to perform the X-Ray imaging of galaxy clusters. The XMM-Newton space telescope (XMM) has been in orbit collecting data since 1999. XMM-Newton carries three very advanced X-ray telescopes. They each contain 58 high-precision concentric mirrors, nested to offer the largest collecting area possible. These mirror modules allow XMM-Newton

to detect millions of sources, far more than any previous X-ray mission. Each mirror module focuses x-ray photons on separate XMM detectors. The cameras used for this analysis are the European Photon Imaging Cameras (EPIC) MOS1, MOS2, and PN cameras.

The publicly accessible source catalog of the European Space Agency XMM-Newton space telescope was searched for observations of regular galaxy clusters. A list of XMM observations of regular galaxy clusters is compiled and from this list a final cluster is chosen to be analyzed. A cluster on which gravitational lensing data has already been performed would be an ideal candidate since this will provide a redundancy in the mass calculation. The data extracted from the XMM source catalog can be reduced and analyzed to obtain temperature and emissivity information for the cluster. This information can then be used to calculate the mass of the cluster by implementing the hydrostatic equilibrium equation. After the mass is calculated comparisons can be made to mass calculated through other methods. Lastly this information may be useful in determining the dark matter distribution of the galaxy cluster since the dark matter is responsible for the majority of the gravitational potential.

1.1 Theory

About ninety percent of the matter in the universe (and likewise in galaxy clusters) is of an unknown kind. This statement is illustrated by the fact that in galaxy clusters the velocities of individual galaxies within the cluster

are far greater than the velocities that could be supported by the observed mass alone [2].

Regular galaxy clusters are relaxed clusters that have not undergone recent mergers. These regular clusters are considerably more spherical than non relaxed clusters [7] and are therefore more suited to modeling as a thermal plasma in hydrostatic equilibrium. The gas in galaxy clusters is typically twenty to forty percent Solar abundance (compared to hydrogen). The high temperature environment in this gas results in thermal Bremsstrahlung radiation. High energy electrons collide with highly ionized and equally energetic atoms producing X-Ray photons. The gas is very diffuse and therefore transparent to radiation so the x-rays can be detected from above our atmosphere. Since the intensity of the radiation is proportional to the square of the gas density [1], the gas density can be calculated. The temperature of the gas can be determined by fitting the x-ray spectra to a thermal bremsstrahlung model.

$$I(E, T) = A\mu G(E, T)Z^2 n_e n_i (kT)^{-1/2} e^{E/kT} \quad (1)$$

This equation allows us to calculate the mass of the x-ray emitting gas, using the cluster luminosity as input. Since the temperature and the mass density of the gas are both now known the mass can be calculated using the hydrostatic equilibrium equation .

$$M_T(r) = \frac{-k_B T r}{G m_p} \left(\frac{d \ln \rho_g}{d \ln r} + \frac{d \ln T_g}{d \ln r} \right) \quad (2)$$

This mass represents the total mass of the cluster responsible for creating the gravitational potential and is derived by balancing the inward gravitational pressure with the outward thermal pressure.

2 Methods

2.1 Data Acquisition

The process of generating usable information from the raw telescope data acquired from the XMM-Newton observatory involves many steps but before any data analysis could begin we had to make a selection of which object to study. With the recent publication of the 1XMM source catalog in April of 2003 a partial list of all the galaxy clusters observed by XMM-Newton was made available to the public. The first task was to search this extensive source list (approximately fifty-six thousand entries) and decide which sources were known galaxy clusters. We decided that an initial selection criteria was that the object must be listed in the NASA/IPAC Extragalactic Database (NED). The original source catalog file contained the NED names of the objects (assuming they were named objects). A program was written to compare a list of NED galaxy names to the names of the sources observed with the XMM-Newton telescope. This comparison resulted in a list of thirty two objects. The resultant list was then searched for a suitable galaxy cluster. Abell 2204 was chosen from this list. Abell 2204 is a relaxed, regular galaxy cluster at a redshift of 0.152. Mass calculations of Abell 2204 have previously

been performed using gravitational lensing data [3] which made Abell 2204 an even more appealing candidate.

The XMM-Newton observation of Abell 2204 was performed on September 12, 2001 over 40 ks for the PN and MOS cameras. After Abell 2204 was chosen the next project was to acquire all the Flexible Image Transport System (FITS) files associated with this observation. Several stages of data reduction were performed on the original FITS files, many of which were handled in the Pipeline Processing System (PPS) created by the XMM Scientific Operations Center (SOC). The pipeline process created a photon event list that was further reduced by removing channel counts caused by solar proton flares.

2.2 Data Analysis

After the data were reduced to the furthest extent, analysis of that data began. Because of the moderate energy resolution of XMM-newton MOS and PN cameras ($E/\Delta E \sim 20 - 50$) the output spectrum can not be inverted so it must be modeled. After a spectrum was generated, it was fitted with a thermal plasma model to determine the temperature of the plasma. Once the temperature was determined the outward thermal pressure was calculated and used to determine the inward gravitational pressure by making the assumption that the cluster was in hydrostatic equilibrium. A mass profile of the cluster was created (see figure 4) using the calculated gravitational pressure.

A light curve was created for each event list at low (.3-10keV) and high (10-15keV) energies. The high energy light curve was used to filter out proton flare events because of the relatively low count rate above 10keV. Since the thermal gas in the galaxy cluster has a constant intensity the light curve should be relatively flat for the entire observation. Any abnormally high spikes in the light curve are likely caused by proton flare events that affect the detector and provide undesirable background. A level of 1.4 counts/sec was chosen for both MOS cameras and 1.1 counts/second for the PN camera, any observation times that host a higher count rate were removed and the result was an effective observation time of 14 ks for PN and 20ks for both MOS1 and MOS2 cameras. All events in a circular region of 10.3 arc minutes around the center of the cluster were selected to perform further analysis. A background spectrum was selected from a sourceless region of the same exposure and subtracted from the region of interest. With the PN camera the background subtraction caused a downward spike in the spectrum at 8keV due to differences in chip construction on the camera [4]. This central region was further divided into eight concentric rings (see figure 1) and a spectrum was extracted for each of these regions separately. Since the cluster is a three dimensional object but the detected photons were only resolved in two spatial dimensions a re-projection matrix is used to normalize these concentric regions appropriately. Each of these regions had comparable counting statistics (9-14 thousand counts) and contained events detected by each of the three cameras. The Wisconsin absorption model was used in conjunction with the Mekal model for fitting of the spectra [6]. The fitting was performed

with the Xspec program. Since the telescope can not perfectly resolve the energy of the detected photons a redistribution matrix file (RMF) and ancillary reconstruction file (ARF) were used to adjust the model spectra to what it would look like if it had been measured by the telescope [5]. It is this adjusted model that was used to fit with the spectra. Initially the spectra were fit as isothermal (see figure 1) and then later fit with separate temperature regions. The temperature of the cluster was determined by fitting the spectra to the Mekal model. The temperatures were used as an input to a program that calculated the radial mass profile by using the hydrostatic equilibrium equation. After the temperature profile was determined (see figure 3) and the gas density was calculated for each region, the mass profile for the cluster was calculated (see figure 4).

3 Results

The spectrum for Abell 2204 was generated using data from all three EPIC cameras. This spectrum was fit to the Mekal and Wisconsin absorption models (figure 2). It was observed that Abell 2204 has a relatively cool core (3.5keV) and an average temperature of 6.5keV. The temperature profile was determined and is expressed in figure 3. The temperature profile consists of eight data points representing the average temperature in eight concentric regions of Abell 2204 out to a radius of about five arc minutes which corresponds to approximately 500 kpc. All data points in the temperature plot are at the ninety percent confidence level. The mass profile was determined

out to 400 kpc and is plotted in figure 4. All data points on the mass profile plot are at the ninety percent confidence level.

4 Conclusions

From these results we can see that the gas accounts for less than ten percent of the total cluster mass in Abell 2204. We can also see how the gravitational potential is distributed throughout the cluster so we can get an idea of how the dark matter is distributed. The mass profile is in good agreement with that obtained through gravitational lensing data [3]. The mass profile is also compared to that obtained using the mass profile of Navarro, Frenk, and White (the NFW profile) [8]. The NFW profile is based on N-body simulations of cold dark matter halos. The disagreement with the NFW profile near the cluster center is due to cooling flow effects in Abell 2204. When the gas density at the center of a cluster is high a significant amount of energy is lost due to x-ray emission. This energy loss results in cooling of the gas and pressure drop in the central region. The gas sinks further into the cluster potential well. The density of the gas in the core region increases and since the rate of radiation goes as the square of the gas density, energy is radiated even more rapidly, which results in a relatively cool central region. [1] These results represent a good initial analysis of Abell 2204 but this is only the first step in a much more detailed and extensive process. Since the hydrostatic equilibrium equation uses the temperature and the temperature gradient as an input more accurate spatial resolution of the cluster temperature is desir-

able. The current analysis subdivides the cluster into eight different regions of roughly equal statistics however this cluster could be subdivided even further into smaller regions to perform a more accurate analysis. Further subdivision of regions may also allow for testing the validity of the apparent spherical symmetry of the temperature distribution in Abell 2204. The PN camera out of time (OOT) events were not accounted for due to time constraints therefore removing these OOT events would be an essential part of any further analysis. Many other clusters of galaxies need to be analyzed in order to gain statistically significant data about the distribution of dark matter in the universe.

5 Acknowledgments

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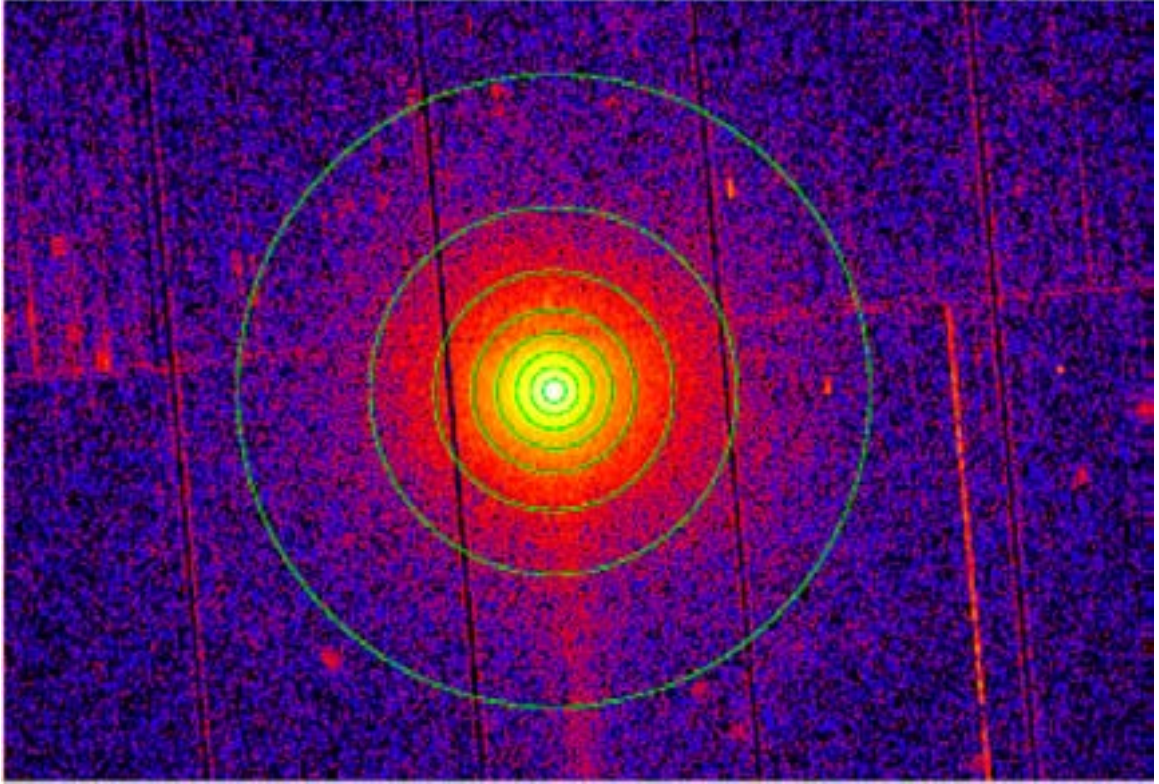
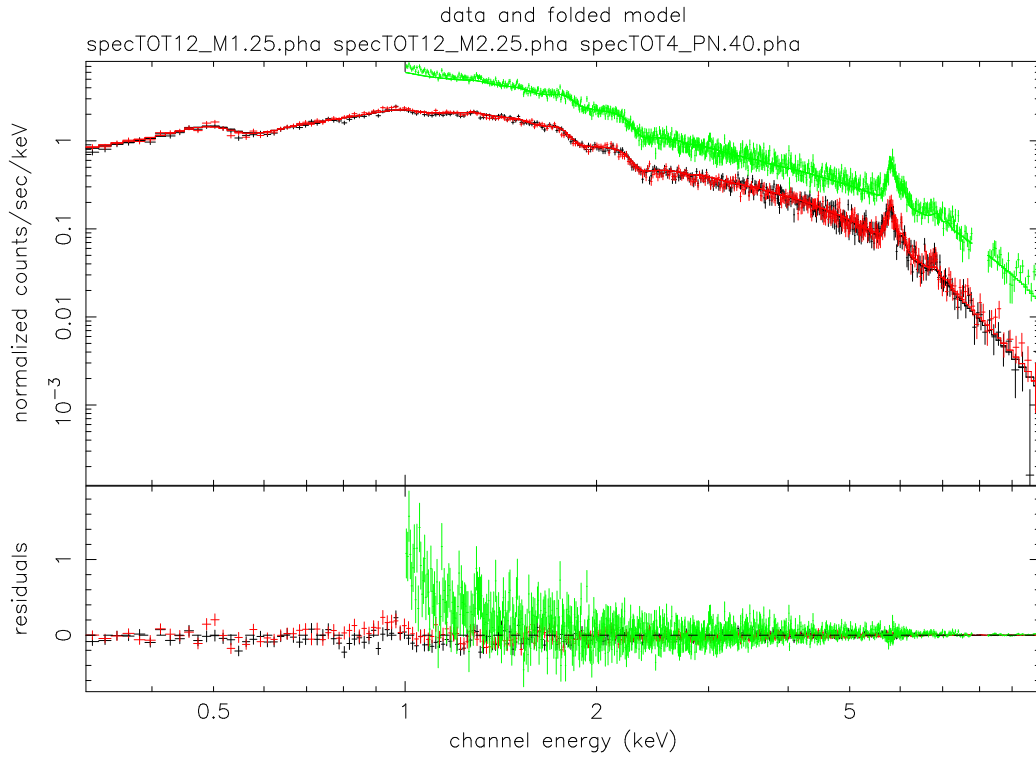


Figure 1: PN image of Abell 2204: This image was generated by binning the calibrated events list of the PN camera in block 64 bins and scaling logarithmically using ds9. The intensity gradient is expressed in false color and the concentric rings show the separate regions mentioned in section 2.2.



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Figure 2: Isothermal Spectrum for Abell 2204: The modeled spectrum for MOS and for PN cameras and the best fit are plotted. The region from 7.8-8.2keV has been removed from the PN spectrum due to reason discussed in section 2.2. The 7keV iron emission line is evident in both spectra.

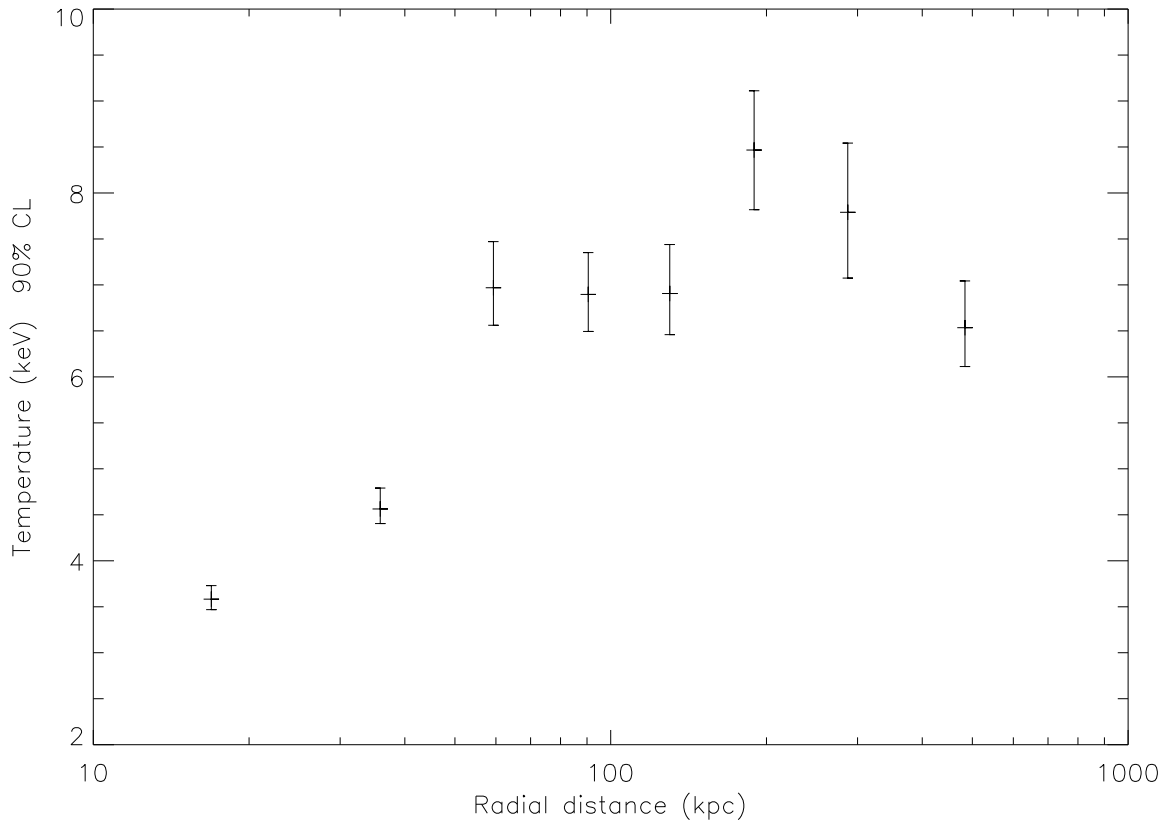


Figure 3: Radial Temperature Profile for Abell 2204: Average temperature was calculated for each separate region of the image and plotted on a logarithmic plot as Temperature (keV) vs. Radial distance (kpc). All data are at the ninety percent confidence level. The low temperature in the cluster core is indicative of a cooling flow cluster.

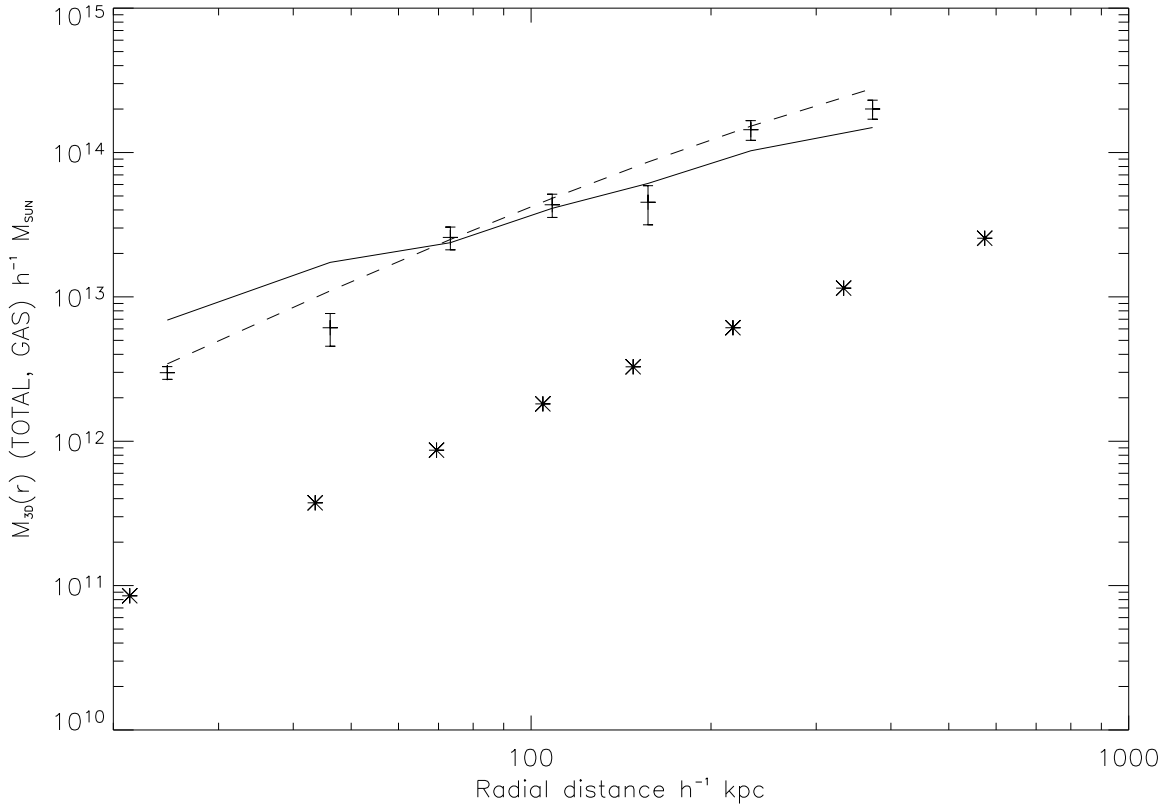


Figure 4: Radial Mass Profile for Abell 2204: Integrated cluster mass is calculated at radii between the analyzed concentric regions. Data are plotted at the ninety percent confidence interval. The dashed line represents mass calculations based on gravitational lensing data from Clowe and Schneider. The straight line is the NFW result from a numerical N-body simulation and is discussed in the conclusions section. The points plotted roughly 1.5 decades below the data represent mass profile due to the gas alone.