A Cluster of Galaxies, Abell 496

F. Nobels and W. Mulder
MSc Astronomy & Kapteyn Astronomical Institute, University of Groningen
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As part of the course High-Energy Astrophysics, data of the Cluster of Galaxies Abell 496 gets analyzed by using the program xspec. From the models fitted in xspec the temperature distribution and number density distribution was fitted, from this the mass of the cluster was found to be $M_{\text{cluster}} = (7 \pm 3) \times 10^{14} M_{\odot}$ assuming the radius of the cluster is around 0.4 Mpc. Furthermore the abundances of multiple elements (Fe, O, Si, Mg and Ne) were fitted in the cluster. From this it was found that the elements that are related to SNe II are almost evenly distributed over the cluster, while elements related to SNe Ia are found more closer to the center of the cluster. This indicates that more older elliptical galaxies are found in the center while young spiral galaxies are found more evenly distributed over the cluster. Finally, one final false color image is created and five images are created having contour plots by the use of the ESA’s script package images and ds9. For comparison one contour plot is overlaid on top of an optical image of Abell 496.

I. INTRODUCTION

The Abell 496 cluster of galaxies is one of the clusters included in the Abell catalogue containing more than 4,000 clusters of galaxies. The Abell 496 cluster is located at a redshift of 0.03 and is included in many X-ray studies [1]. This study is done by analyzing the data of XMM-Newton (X-ray Multi-Mirror Mission - Newton). The XMM-Newton is a X-ray satellite property of the European Space Agency launched in 1999. This report will exist of a few sections. The first section will contain a short summary of information and previous work concerning the Cluster of Galaxies Abell 496. In the second section the data will be analyzed by the use of a model defined in xspec. In the third section results of the data analysis will be given. Section four will contain the color image and contour plots made using the ESA’s script package images. In the last sections there will be given a discussion and a final conclusion.

II. DATA ANALYSIS

During this project data from a XMM-Newton observations of Abell 496 was used. This data contains information about the cluster which is separated into seven rings, each having his own spectra. The spectra are ordered from the center to the outer ring of the cluster. A overview of the available data is shown in Table I.

There is a corresponding background spectrum for each ring, and a response matrix for each spectrum.

1. Defining the Model

In order to work with the data, a model has to be defines using model components of the X-ray Spectral fitting package, xspec. Combining the $\text{vapec}$ and $\text{wabs}$ components will create a model which can describe the XMM-Newton data accurate.

\[ \text{model} = \text{projct} \times \text{wabs} \times \text{vapec} \]

- $\text{Vapec}$ is a model component which is able to describe an emission spectrum from collisionally-ionized diffuse gas. Knowing that the emission of clusters of galaxies is well described by a plasma in Collisional Ionization Equilibrium, meaning the state of ionization of the plasma being determined by collisions between the ions and electrons in the plasma, $\text{vapec}$ is being used. The emission mechanism that is present in the cluster is Bremsstrahlung, which is also covered in $\text{vapec}$. When $\text{vapec}$ is used it will return the temperature for every ring, together with the normalization ($\text{norm} = f(\rho)$) and abundance for multiple elements of this ring. This allows users to look for the abundances, temperature and density in the cluster. In this way plots can be created for these parameters.

- $\text{Wabs/phabs}$ is a model component used to describe the photo-electric absorption between the telescope and the galaxy cluster.

- $\text{Projct}$ is a 3D to 2D projection model, which means that all the inferred parameters are in 3D space and not in the projected 2D plane.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Radius</th>
<th>Exposure time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-16</td>
<td>7153</td>
</tr>
<tr>
<td>2</td>
<td>16-32</td>
<td>7153</td>
</tr>
<tr>
<td>3</td>
<td>32-48</td>
<td>7152</td>
</tr>
<tr>
<td>4</td>
<td>48-128</td>
<td>7151</td>
</tr>
<tr>
<td>5</td>
<td>128-384</td>
<td>7130</td>
</tr>
<tr>
<td>6</td>
<td>384-512</td>
<td>7101</td>
</tr>
<tr>
<td>7</td>
<td>512-800</td>
<td>7075</td>
</tr>
</tbody>
</table>

TABLE I: XMM-Newton data
In the first part of this report vapec was used with equal abundance for all elements. From this model, the mass of the galaxy cluster itself was determined. After this vapec was used with different abundances for Fe and from this every element of interest was fitted one from one together with Fe. The elements of interest were selected to be O, Si, S, Mg en Ne.

III. RESULTS

By fitting the model described in II 1, the different parameters of the model for every ring could be inferred. This consisted of the temperature, abundance and normalization constant of every ring (normalization constant is function of density). From these values functions for these parameters could be fitted through the the temperature and density to determine the mass of the galaxy cluster.

For the distance the fact was used, that the optimal distance is between 2 distances is given by the expectation value of the two, which means that the distance is given by,

$$\langle r \rangle = \frac{\int_{r_1}^{r_2} r \, dV}{\int_{r_1}^{r_2} dV} = \frac{3}{4} \frac{r_2^4 - r_1^4}{r_2^3 - r_1^3}$$

A. Temperature profile

From the inferred temperatures from the model, it can be seen that the temperature could be best fitted by a function which exponentially reaches a constant value and than decreases linearly, the the proposed temperature profile is,

$$T(r[Mpc]) = a + b \exp(-c \cdot r[Mpc]) - d \cdot r[Mpc].$$

This resulting fit is showed in blue in figure 1. For the fitting values see table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$5.4 \pm 0.7$ keV</td>
</tr>
<tr>
<td>b</td>
<td>$4.0 \pm 0.7$ keV</td>
</tr>
<tr>
<td>c</td>
<td>$(12 \pm 3)$ Mpc$^{-1}$</td>
</tr>
<tr>
<td>d</td>
<td>$(5 \pm 2)$ keV Mpc$^{-1}$</td>
</tr>
</tbody>
</table>

B. Density profile

In the case of the density profile it is a bit more complicated, because during the model fitting not the densities were found, but the normalization constants. From vapec it is known that the normalization is given by,

$$\text{norm} = \frac{10^{-14}}{4\pi \cdot (1 + z) \cdot D_A^2} \int n_e n_H dV.$$  

In which, $z$ is the redshift, $D_A$ is the angular diameter distance to the source (in cm). Furthermore $n_e$ and $n_H$ are the electron and hydrogen number densities. This equation can be rewritten under the assumption $n_e = n_H$ and using discretization to rewrite the number density to,

$$n_H = \sqrt{\frac{4\pi \cdot (1 + z)^2 D_A^2 \cdot \text{norm} \cdot 10^{14}}{\Delta V}}.$$  

In which $\Delta V$ is the volume of one ring in physical units. From this the number density for each shell was calculated, this was fitted using an ordinary power law given by,

$$n(r[Mpc]) = a \cdot r[Mpc]^{-b}.$$  

This resulted in the blue fit shown in figure 2. For the fitting values see table III. It is noted that for the calculation of the cluster the density in g cm$^{-3}$ is not necessary to calculate because this is given by $\rho = \mu m_H \cdot n$, and this term cancels out in $\frac{d \log \rho}{d \log r}$, so $\frac{d \log \rho}{d \log r} = \frac{d \log n}{d \log r}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$(7 \pm 1) \cdot 10^{-4}$ cm$^{-3}$ Mpc$^5$</td>
</tr>
<tr>
<td>b</td>
<td>$0.94 \pm 0.04$</td>
</tr>
</tbody>
</table>
C. Mass profile

In order to be able to create a mass profile for Abell 496, it is assumed that Abell 496 is in hydrostatic equilibrium, this means that the mass profile is given by,

$$M(R) = \frac{kT(r)r}{G\mu m_p} \left[ \frac{\partial \ln T}{\partial \ln r} + \frac{\partial \ln \rho}{\partial \ln r} \right]. \tag{6}$$

In this expression, the derivatives with respect to temperature and density can easily be calculated [4] and from these the log derivatives can be calculated straightforward [5]. From equation also the error in the mass can be calculated, this is a very long straight forward calculation, which will not be discussed completely, but the idea is that the error is given by,

$$\sigma_f = \sqrt{\sum_{i=1}^{N} \sigma_i^2 \left( \frac{\partial f}{\partial x_i} \right)^2} \tag{7}$$

In which $f = f(x_1, \ldots, x_N)$, thus $f$ is a function from other functions with their error. From this the error is calculated in the mass. This resulted in the following mass profile shown in figure 3.

From this plot the mass of Abell 496 is found to be $M_{\text{cluster}} = (7 \pm 3) \cdot 10^{14} M_{\odot}$, assuming the cluster has a size of 0.4 Mpc.

D. Abundances

In the X-ray spectrum of the cluster emission lines are being detected. This confirms the presence of heavy elements in the inter cluster medium. These heavy elements in the ICM can not be only from primordial origin. By knowing that different types of supernova explosions will create different heavy elements, the emission lines of the elements Fe, O, Si, S, Mg turn out to be important. [2] Therefore, it seems useful to look for the distributions of these metals over the cluster. Using the model component $v_{\text{pec}}$, all the ‘important’ abundances are determined for each ring, in order to be able to compare the different abundances, a straight line is fitted through the data points ($Z_{\text{element}} = a \cdot r + b$).

![FIG. 2: The density profile of Abell 496.](image)

![FIG. 3: The mass profile of Abell 496.](image)

![FIG. 4: The overall abundances of Abell 496 (best fits).](image)

### TABLE IV: All fitted values for metal abundances

<table>
<thead>
<tr>
<th>Metallicity</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>overall</td>
<td>$-1.1 \pm 0.2 Z_{\odot} \ Mpc^{-1}$</td>
<td>$0.51 \pm 0.03 Z_{\odot}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$-0.9 \pm 0.2 Z_{\odot} \ Mpc^{-1}$</td>
<td>$0.54 \pm 0.04 Z_{\odot}$</td>
</tr>
<tr>
<td>O</td>
<td>$1.6 \pm 2.0 Z_{\odot} \ Mpc^{-1}$</td>
<td>$1.6 \pm 0.5 Z_{\odot}$</td>
</tr>
<tr>
<td>S</td>
<td>$-5 \pm 3 Z_{\odot} \ Mpc^{-1}$</td>
<td>$1.0 \pm 0.3 Z_{\odot}$</td>
</tr>
<tr>
<td>Si</td>
<td>$-2.7 \pm 0.9 Z_{\odot} \ Mpc^{-1}$</td>
<td>$1.0 \pm 0.2 Z_{\odot}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$-1.6 \pm 1.2 Z_{\odot} \ Mpc^{-1}$</td>
<td>$0.8 \pm 0.3 Z_{\odot}$</td>
</tr>
<tr>
<td>Ne</td>
<td>$-0.3 \pm 1.3 Z_{\odot} \ Mpc^{-1}$</td>
<td>$1.4 \pm 0.3 Z_{\odot}$</td>
</tr>
</tbody>
</table>

Presence of a SNIa Other studies [1] indicates that the Type Ia supernovae (SNe Ia) produce large amounts of Fe, Ni and the elements Si, S, Ar, and Ca. In the case of a SNe Ia, often there is just a little amount of O, Ne and Mg present.
Looking at the abundances plots, it becomes clear that the Abell 496 cluster of galaxies contains emission from the elements Si and S.

**Presence of a SNII** According to [1] when looking for Type II supernovae (SNe II), the oxygen abundances is important due to the fact that O is primarily originated from these SNe II. Besides the amount of Oxygen created, SNe II also create large quantities of Ne and Mg.

Again from looking at the total abundances in Figure 4, the conclusion can be made that there is a large amount of Oxygen present. In addition, there is Ne and Mg present.

To conclude, the abundances of heavy elements suggest the presence of supernovas. Due to the emissions of the heavy elements and the fact that there is a change in the O/Fe ratio, it is suggested that both SNe Ia and SNe II are present in the cluster of galaxies. [1]

From the abundances of Oxygen and Neon can be concluded that the locations of the SNe II is equally distributed over the cluster. This is also approximately consistent with the fitted function for Magnesium. While the other abundances are more present in the center and related to the presence of SNe Ia. This is consistent with the current view on the properties of clusters. The older elliptical galaxies will be located near the center of the cluster, where most SNe Ia elements are found. In addition, the younger, mostly spiral, galaxies will be distributed over the whole cluster, just as seen in the abundances of the other heavy elements related to SNe II.

**IV. FALSE COLOR IMAGE AND CONTOUR PLOTS**

In order to be able to create X-ray images in several energy bands, the script ‘images’ is used. The script can create the different images by combining data from the XMM-Newton pn and MOS cameras.

The images script is run from an Observation Data File data set, ODF, folder. By changing the parameters in the image input file, we are able to run the script from start to end. The script is designed to process the data in different stages. First we have initial processing which includes producing events lists from the ODF file and gti-cleaning. Secondly pn images and exposure maps are created, thirdly MOS images and exposure maps are created and finally the MOS and pn images are combined to five final images. These images all show different energy bands ranging from soft till hard bands.

**A. False color image**

The color image is made by loading the data with ds9 into a special RGB frame. This frame is creating red, green and blue filters. The red band is defined to be the soft X-ray-band, the green is the medium X-ray-band and the blue is the hard X-ray-band. Eventually the frame will contain all three color files stacked together.

**B. Contour plots**

Figure 6 shows the five images created separately. The images are ranging from soft band in the left upper corner till hard-band in the right lower corner. As reminder, when creating an image, the first image is used as the red frame, the third as the green and the last as the blue frame.

Plotting contours shows the flux distribution. The contour plots show the flux levels $0, 2\times10^{-5}, 4\times10^{-5}, 6\times10^{-5}$ and $8\times10^{-5}$. In Figure 7 a comparison is shown between the created medium X-ray image and a fits file obtained from the Nasa/IPAC Extragalactic Database. The contour plots are those of the medium X-ray band as shown in Figure 6.

**FIG. 5:** Color image made by using ds9.

**FIG. 6:** Using ds9, contours were added to the images created by the images script.
V. DISCUSSION

It was found, during the use of xspec that fitting models is very sensitive to fluctuations of the different parameters, meaning that the norm fluctuations in such a way, that fitting different norms may result in differences of the log derivative with a significant factor. Which means that the determination of the mass in reality has a larger error than shown in figure 3, because of an intrinsic error in the model itself. Furthermore, the models which were used and the made assumptions, assume certain things which might actually not be true, but are a simplification of reality. Because of this certain parameters of the model which are set equal over all rings, have actual distinct values, and because of this a better model needs these different parameters.

VI. CONCLUSION

In this report a temperature distribution and number density distribution was found and used to determine the mass of Abell 496. The mass of Abell 496 was found to be $M_{\text{cluster}} = (7 \pm 3) \cdot 10^{14} \, M_\odot$, assuming the size of the cluster is around 0.4 Mpc. Furthermore the abundances of multiple elements were found and fitted. From this abundances it was found, that elements related to SNe Ia are present more prominent in the center while elements related to SNe II are found to have a more equal distribution over the cluster. This confirms the current view on clusters that in the center of clusters older elliptical galaxies are present. While over the whole cluster, spiral galaxies are distributed with young stars.


[3] This assumption is very good because plasma in general is neutral overall and completely ionized.

[4] $\frac{dT}{d\log r} = -b \cdot c \cdot \exp(-c \cdot r) - d$ and $\frac{d\rho}{dr} = -b \cdot a \cdot r^{-b-1}$.

[5] $\frac{d\log T}{d\log r} = \frac{r \frac{dT}{T}}{r \frac{dr}{r}}$. 