Galaxy Cluster MACSJ0417.5-1154
Determining Mass Distribution by Gravitational Lensing

Megan Geen
Wheaton College

Advisors: Maruša Bradač, Chris Fassnacht, Nicholas Hall

October 26, 2010

Abstract

To determine galaxy cluster, MACSJ0417.5-1154's mass distribution we analyzed its strong lensing effects. Its mass distribution is of interest because it is the post-merger of one massive and one less massive galaxy cluster. We want to see how the dark matter of each cluster interacts during the merger. To find the mass distribution we looked at three stars that were strongly lensed into multiple images and arcs using Hubble Space Telescope and Subaru Telescope Images in ds9. Then using LensTool we were able to use analytical methods to model the cluster and stars to predict the source positions of the stars and the critical curves of the lens. From these two results we were also able to derive a fits file mapping the mass distribution of the cluster. For this information, further study of MACSJ0417.5-1154 can be done involving its use as a magnifier to study high red-shift galaxies.

Introduction

MACSJ0417.5-1154 is a 0.443 redshift galaxy cluster found in the constellation Eridanus. Like the well known Bullet Cluster[1], MACSJ0417.5-1154 is an example of a post-merger of two clusters. This means that the two clusters involved, one massive cluster with a cD galaxy and one smaller cluster, have already passed through each other. X-ray analysis of the cluster has confirmed this. The effects of the merge can be observed in the Subaru images of the cluster by the tail of interstellar gas between what is thought to be the three main galaxies in the two clusters.

To learn more about this cluster we want to know the mass distribution of the cluster. By knowing this piece of information we would be able to further see how galaxies evolve through collisions. We would also learn more on how dark matter, the most massive and invisible part of all clusters, interacts during a merger. Furthermore, by knowing the mass distribution we can make a magnification map. This allows us to know how well an object's light gets magnified, so we will be able to observe and study high redshift galaxies. These galaxies are on the edges of our universe, thus their light that is just reaching us is from the beginning of star and galaxy formation.

In order to determine the mass distribution of MACSJ0417.5-1154, we used strong gravitational lensing. Gravitational lensing is when a very massive and dense object such as a galaxy cluster is in the direct path of another object's light to us. The light is then bent around the cluster because this is now the shortest path to us due to general relativity. Now the object's light is coming at us from a new angle making it seem that the object is located in a different part of the sky. General relativity also tells us there is another shortest path the light can take to us creating another image in the sky of the object. The creation of multiple images of the same object is strong gravitational lensing. By analyzing the effects of gravitational lensing, we study the entire mass of the lens (the galaxy cluster). This is useful because of dark matter. Dark matter makes up about eighty percent of all matter in the universe and calculations show that a galaxy cluster has ten times more mass than the mass of its visible matter. As a result, gravitational lensing is a sufficient way to calculate the mass of both the visible matter and dark matter in a galaxy cluster[3].

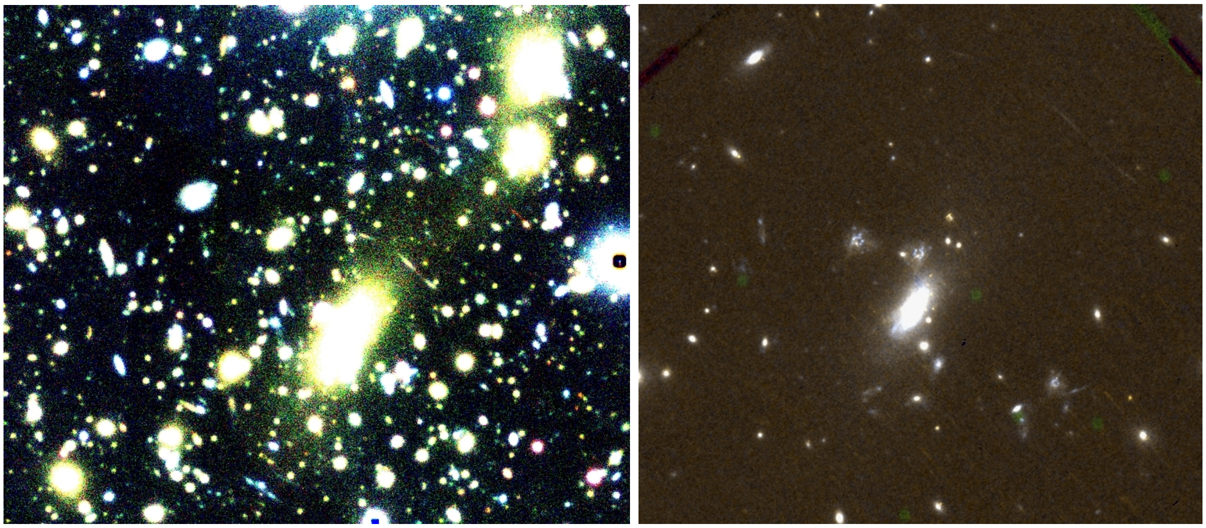

Figure 1: (left) Subaru image of MACSJ0417.5-1154. The three dominant galaxies are shown with a tail of interstellar gas between them. **(right)** HST image of the cD galaxy. Multiple images include arcs in upper-right, three circular-objects above and to the right of cD galaxy, and three dot with a tail objects under, to the right and left of cD galaxy.

Methodology

In order to study this cluster we received images from the Hubble Space Telescope and the Subaru Telescope in Hawaii. Images from these telescopes are actually FITS (Flexible Image Transport System) files that contain the flux at each pixel or point in the sky. Telescopes actually measure the amount of light the hit their detectors at certain wavelengths. The filters we received were F606W, F814W, and a small composite of the two from HST and V (500-600nm), R (600-700nm), and I (750-875nm) from Subaru. By designating these filters certain parts of the spectrum (red, green, or blue) in ds9, we are able to get color images of the cluster. It is with these images that we are able to study MACSJ0417.5-1154.

When first starting to study a galaxy cluster, we want to indentify cluster members. All cluster members are in the same spatial plane thus all have the same redshift. Also most galaxies are elliptical so the have approximately the same coloring to them. So even with a large redshift, all galaxies that are cluster members should have the same color. So we want to look at the Subaru images because they make all objects seem larger with more distinctive coloring, allowing us to identify members easier. So we identify our three main galaxies, note their color (RGB values) and find other members close by with similar color. We then catalog these members by center position, semi major and minor axis, angle, and apparent magnitude.

Next we need to identify multiples of the same image to analyze the gravitational lensing. . Multiple images have the same shape and color to them so we want to use HST images to look at the details of possible multiple images. Around the massive central galaxy, we can see three groups of three multiple images. The first multiple is donut shaped with five distinct knots that are individual objects. Two of the images are above the central galaxy and the third is to the right. The second multiple consists of what looks like a dot and tail. One is located to the left of the upper donuts; the second is below the central galaxy with the third to the right of this image near the third donut. Finally the last multiple is a group of three arcs to the northeast of the central galaxy. Like the cluster members, we catalog these images by position, semi major and minor axis, angle, and redshift. These catalogs are then used along with a parameter file in a program called LensTool. LensTool uses these files to model the cluster. The parts we are interested in that help us model the cluster are the lensed image locations, source image locations, and critical and caustic curves.

Critical and caustic curves determine how strongly an object is lensed. Critical curves are found on the image plane with the galaxy cluster and are the points of maximum magnification. Caustic curves are the critical curves lensed backwards on to the source plane where the original object is located. Each redshift has its own set of critical and caustic curves around the galaxy or galaxy cluster that is acting as a lens. Every time a source crosses a critical curve, another two images appear making multiple images occur in odd multiples. When an image is lensed, each multiple image has to alternate being inside and outside the critical

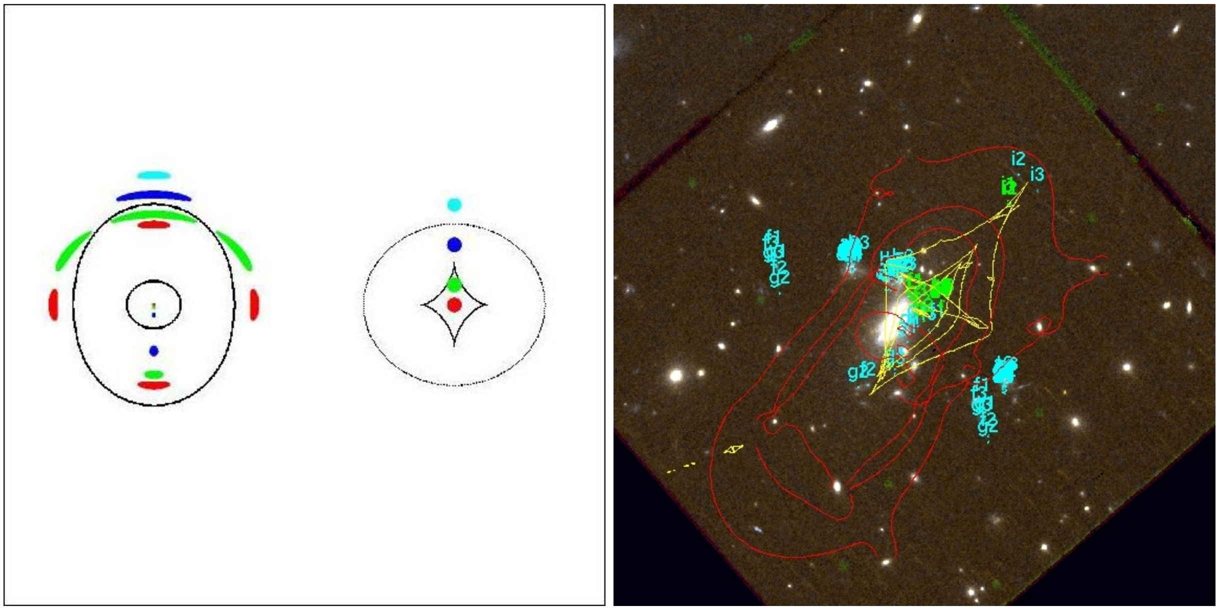

Figure 2: (left) Lines on the left are caustic curves with four source images depicted as colored dots. On the right are the corresponding critical curves with the lensed images[2]. **(right)** Model of the galaxy cluster with three sets of lensed image locations, source image location, and critical and caustic curves. Lensed image locations are depicted in blue. Source image locations are green. Critical curves are red and caustic curves are yellow.

curves. Also the closer a source is to the caustic curves, the more stretched and thus arc-like the images become because they are closer to maximum magnification. Figure 2 demonstrates multiple source images and how they get magnified. Note that Figure 2 is for a single elliptical galaxy. The critical and caustic curves for a galaxy cluster are not as smooth because there are multiple galaxies affecting these curves.

Results

After optimizing our parameter files, we obtained the model in Figure 2. Shown in this model are the lensed image locations, source image locations, and critical and caustic curves for each of the three lensed images. This model predicts that the lensed images redshifts are 0.87 for the donut, 1.14 for the dot and line, and 1.73 for the arc. The inner critical curve in Figure 2 corresponds to the 0.87 redshift and the outer curve corresponds to the 1.73 redshift.

From this model we can then derive the mass distribution maps shown in Figure 3. We have two mass distribution maps, one of the whole cluster and one of the cD galaxy. In the maps, the areas of highest mass concentration are colored white while areas of lowest concentration are black. Also from the larger map, we got the contour lines of the different mass distribution levels. These we were then able to overlay onto a Subaru image to see were these levels were located around the cluster.

From this data we were then able to extrapolate the total mass of the cluster within circular regions of varying radii. All mass regions are centered on the cD galaxy. At a radius of 550 arcseconds (which covers most of the cluster) the total mass is 777.054 x 10^{12} solar masses. The masses for all radii can be found in Table 1 and Figure 3.

Conclusion

From the larger distribution map we can see that the majority of the mass is distributed between the two galaxy clusters. From the close up, we can also see that the mass is centered on the galaxies themselves rather than the interstellar gas. This means that there has to be some other form of matter that is not visible present around the galaxies that make them more massive than the interstellar gas. The extra invisible matter is

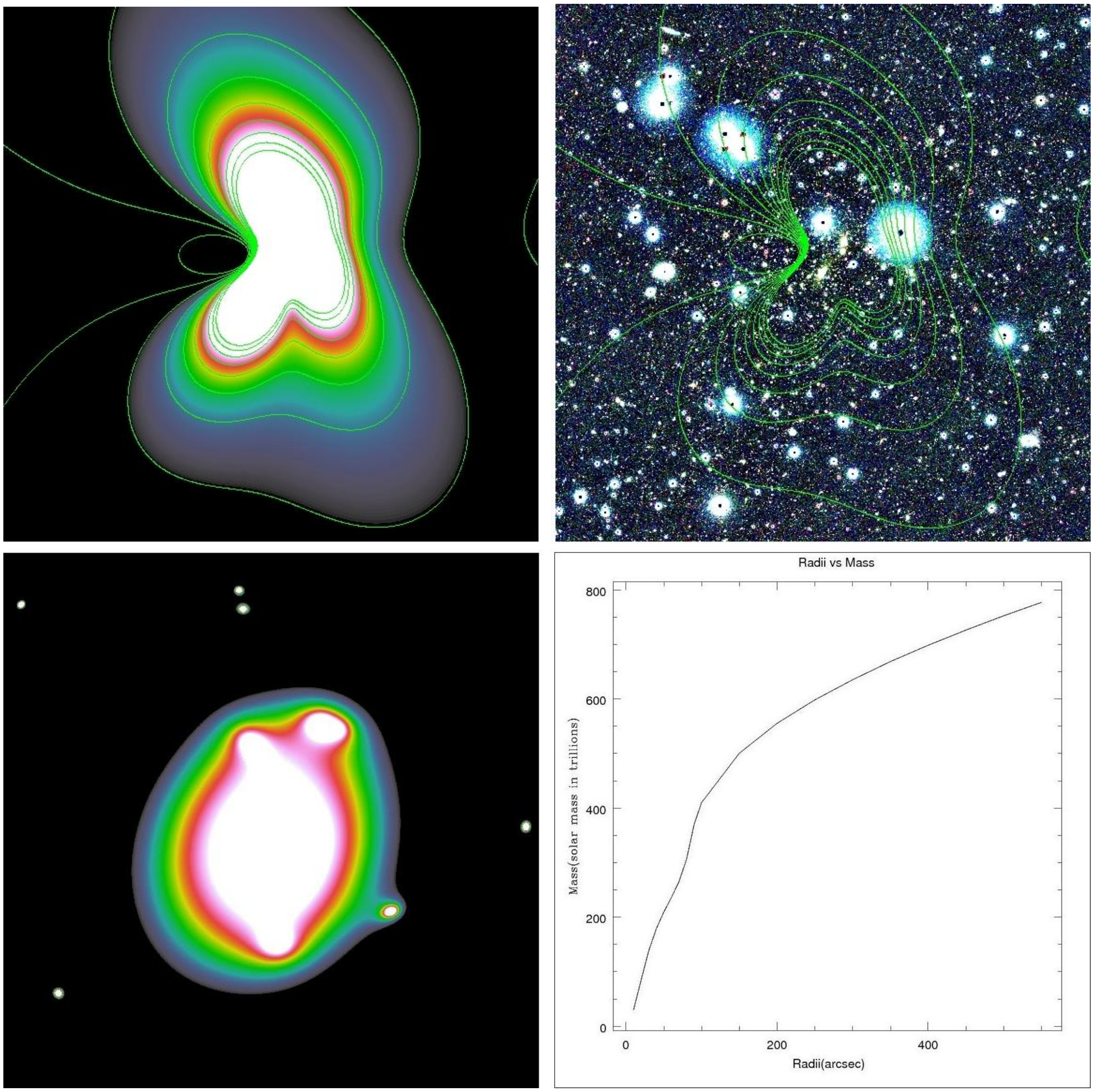

Figure 3: **(upper left)** The mass distribution of the galaxy cluster. White represents areas of most concentration and black represents areas of least concentration. Green contour curves show the different levels of mass distribution. **(upper right)** Corresponding mass distribution contour curves overlaid on a Subaru image. **(lower left)** Close up of the mass distribution of the cD galaxy. **(lower right)** Plot of the mass of the galaxy cluster in solar masses within a circular region centered on the cD galaxy. Radii of the region is measured in arcseconds. Exact numbers are found in Table 1

Radii (arcsec)	**Mass** (solar mass x10^{12})	**Radii** (arcsec)	**Mass** (solar mass x10^{12})
10	29.5533	300	635.430
50	208.830	350	668.420
100	409.724	400	698.496
150	500.425	450	726.362
200	555.180	500	752.442
250	598.424	550	777.054

Table 1: The mass of the galaxy cluster in solar masses within a circular region centered on the cD galaxy. Radii of the region is measured in arcseconds. Plot of this table found in Figure 3

what we call dark matter, and this suggests that dark matter, like the galaxies, passed through the merger unimpeded.

To help support and confirm these results, a weak lensing approach to finding the mass distribution can be done. The weak lensing approach takes in account the shearing of all the objects around the galaxy cluster. By averaging the shearing effect over smaller subsections of the sky, we can obtain a map of the shearing that can be transformed into a map of the mass distribution.

After confirming these mass distribution maps, we can then use them to make magnification maps. This cluster not only bends the light of distance objects around it, but also magnifies them. By knowing how much this cluster magnifies different objects located behind it, we can tell how far away an object is and better determine its redshift. Then we can study object at very high redshifts which are from the early stage of our universe. Studying these objects will help give us insight into star and galaxy formation at the beginning of the universe.

References

[1] M. Bradač, D. Clowe, A. H. Gonzalez, P. Marshall, W. Forman, C. Jones, M. Markevitch, S. Randall, T. Schrabback, and D. Zaritsky. Strong and Weak Lensing United. III. Measuring the Mass Distribution of the Merging Galaxy Cluster 1ES 0657-558. ApJ, 652:937–947, December 2006.

[2] R. Narayan and M. Bartelmann. Lectures on Gravitational Lensing. *ArXiv Astrophysics e-prints*, June 1996.

[3] P. Schneider, C.S. Kochanek, and J. Wambsganss. *Gravitational Lensing: Strong, Weak and Micro.* Springer Berlin Heidelberg, 2006.