8.5: Velocity and Mass Distributions in Galaxy Clusters

What Do You Think: Galaxy Clusters

8.5.1: Observed Motions of Galaxies in Clusters

The motions of stars and gas in galaxies were not the first evidence that galaxies contain enormous amounts of unseen material, or dark matter. They merely confirmed a mostly forgotten result from decades earlier. The first evidence that dark matter dominated over the visible kind dates back to the 1930s, to studies of the Coma galaxy cluster. Fritz Zwicky (1898 - 1974), an astronomer at Caltech (Figure 8.18), had discovered that galaxies tend to cluster together. His discovery contrasted with the beliefs of most astronomers of the time, who thought that galaxies were evenly sprinkled through space. Of course, this belief was not based upon any evidence one way or another. Until Zwicky, no one had really bothered to look carefully.

Figure 8.18: Fritz Zwicky was a Swiss astronomer who worked most of his life at CalTech. He was the first to realize that there must be some “missing mass” in clusters of galaxies that was needed to keep the galaxies from escaping from the cluster. Credit: Courtesy Fritz Zwicky.

To follow up his discovery, Zwicky investigated the galaxies in a large galaxy cluster in the Coma Berenices constellation. The galaxy cluster is called the Coma cluster, after the constellation; Figure 8.19. Zwicky measured the amount of starlight in the galaxies (an indication of the number of stars they contain) as well as the total amount of mass in the cluster. This he determined from motions of the galaxies through the cluster. What he found astonished him.

Figure 8.19: The Hubble Space Telescope's Advanced Camera for Surveys viewed a large portion of the Coma cluster, spanning several million light-years across. The entire cluster contains thousands of galaxies in a spherical shape more than 20 million light-years in diameter, and is over 300 million light years away. Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

Galaxy clusters are a bit like elliptical galaxies, but on a much larger scale. Within elliptical galaxies, stars move in randomly oriented orbits around the center of the galaxy, moving in response to the overall gravity of the galaxy. This includes the gravity from all the other stars in the galaxy, as well as the unseen "dark" matter that makes up most of its mass.

In galaxy clusters, galaxies themselves orbit the center of the cluster in response to the overall gravity of the cluster. We can measure the motions of the galaxies in a galaxy cluster to determine the mass of the entire cluster, similar to the way we measure stellar motions within an elliptical galaxy to determine the galaxy's mass. This is what Fritz Zwicky did to measure the mass of the Coma cluster.

8.5.2: Masses of Galaxy Clusters and Further Evidence of Dark Matter

Although the galaxies in a galaxy cluster have orbits that resemble those of stars in an elliptical galaxy, astronomers use a somewhat different technique to measure the cluster galaxies' motion. In an elliptical galaxy, it is difficult to measure the motion of an individual star, so astronomers look for the signature of the motions of many stars all at once. In a galaxy cluster, however, it is possible to measure the motions of individual galaxies within the cluster. Astronomers can then combine the measurements of the motions of several galaxies in a cluster to get a velocity dispersion measurement of the galaxy cluster as a whole. They then use the velocity dispersion measurement to determine the mass of the galaxy cluster.

To measure the motions of individual galaxies in galaxy clusters, astronomers measure their redshifts, which should not be a surprise. The measured redshift gives them a sense for how fast the galaxies are receding from us. Galaxy clusters as a whole move away from us due to the expansion of the Universe, and because of this we see that all the cluster galaxies have redshifted spectral features. Within a galaxy cluster, a galaxy might be on an orbit that causes its velocity to be slightly larger than that of the cluster as a whole, or on an orbit that causes its velocity to be slightly smaller than that of the larger cluster (see Figure 8.20).

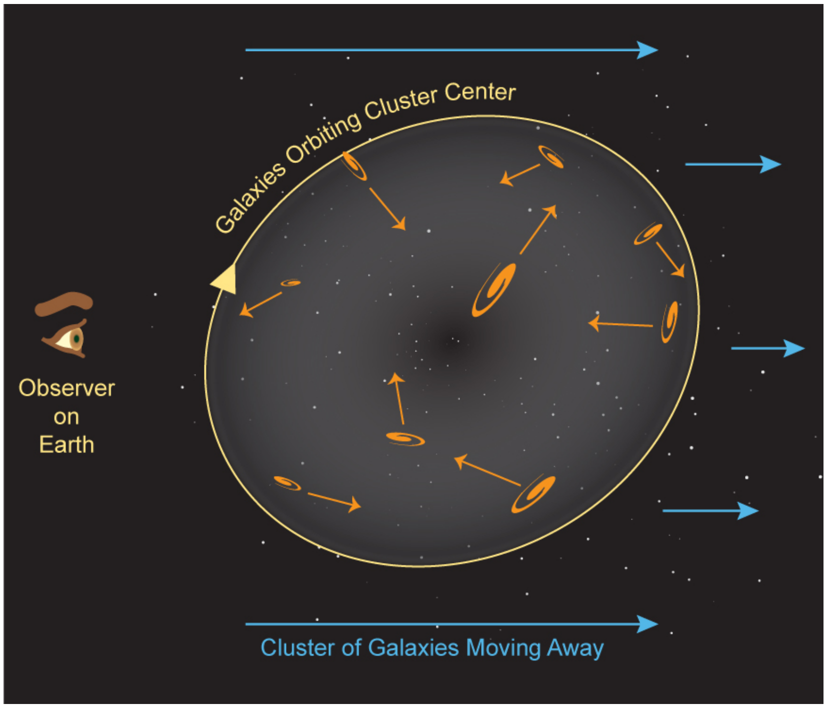

Figure 8.20: This galaxy cluster, as a whole, is moving away from us due to the expansion of the Universe. Within the cluster, some galaxies have even larger velocities away from us due to their orbits within the cluster, and some have slightly smaller velocities away from us. Credit: NASA/SSU/Aurore Simonnet

Remember that when we discussed the motions of stars within elliptical galaxies in Section 8.4.3, we noted that if the stars' velocities were too large, the galaxy's gravity could not hold onto them. In that case they would fly away. Similarly, if a galaxy in a galaxy cluster is moving too fast, the cluster's gravity will not be able to hold onto it, and it would fly out of the cluster. So we know that a galaxy cluster must have enough mass to hold onto any of the galaxies that we observe within it. If it did not, any fast-moving galaxy would most likely have flown away long ago.

Zwicky knew this too, and he used the same expression to relate the mass of galaxy clusters to the galaxy motions as we used for stars in elliptical galaxies in Section 8.4.3:

$$M = k\frac{\langle v^2 \rangle r}{G}$$

Remember that in the equation above, the term in brackets is the mean square of the velocity dispersion. In this case, the velocity dispersion of the galaxy cluster is a measurement of the spread of different velocities of the galaxies in the cluster. The constant k may depend on the shape of the cluster, among other things.

Zwicky found that galaxies move much faster through a cluster than stars move within galaxies. He found that the typical velocity dispersion for the galaxies in the Coma cluster was well in excess of 1000 km/s. The high velocity dispersion implies a very large mass for the cluster. When Zwicky compared the velocity-determined mass of the Coma cluster to the mass expected from the light from the stars in the galaxies, he found that they were very different. This is much like what Vera Rubin found four decades later when she studied the rotation of spiral galaxies.

In order to hold together, the galaxy clusters required much more mass than was evident from the light of just the stars in their galaxies. Zwicky found that most of the mass of a galaxy cluster lies outside of the galaxies themselves, just as most of the mass of a galaxy is not contained in its stars. The following activity lets you perform the same sorts of measurements that Zwicky did to determine the velocity dispersion for the galaxies in a sample galaxy cluster.

Measuring the Velocity Dispersion of a Galaxy Cluster

In this activity, you will have an opportunity to measure the velocity dispersion of the galaxy cluster Abell 2029.

First, you will need to make a histogram, or bar chart, of the redshifts of the galaxies in the cluster.

- The interactive activity has a bunch of galaxy images with numbers printed on them in red. These numbers are actual redshifts of galaxies in cluster Abell 2029 (though the images are simulations).
- To make your bar chart, click on a galaxy image and drag it to the box above the correct redshift range. For example, if the galaxy you clicked on has a redshift of 0.075011, it should go in the box above the redshift range 0.074 - 0.076. Do this for all 16 galaxies pictured.
- Remember that all the galaxies in the cluster are redshifted because the whole cluster is moving away from us due to the expansion of the Universe. However, within the cluster, some galaxies are moving slightly toward us and some are moving slightly farther away, resulting in slightly different redshifts for each galaxy.

Next, you will fit a Gaussian shape to the bar chart to measure the width of the distribution of the cluster galaxies' redshifts.

- Click on the "Next" button to the lower right. You will see that your bar chart gets squeezed a bit to make the Gaussian fitting easier.
- Now click on the box next to "Show Gaussian Tool." This will bring up a Gaussian fitting tool just like the one you used for the elliptical galaxy velocity dispersion measurement, except that the shape is flipped (with the "hill" now pointed upward instead of downward).
- Here are the details of how to use the tool: The tool has a horizontal adjustment and a vertical adjustment. The horizontal adjustment has two large white dots: the dot on the left can be used to move the tool away from its initial position on the y axis. The dot on the right can be used to change the width of the Gaussian shape. The smaller dot on the vertical axis of the tool can be used to change the height of the Gaussian shape.
- Carefully fit the shape of your bar chart for the redshift distribution using the tool. The tool will display the width of your Gaussian shape (sigma) in redshift, and it will automatically convert this number to a velocity dispersion measurement.

Play Activity

The Mass of the Coma Cluster

We can do a calculation to learn more about the mass of the Coma cluster. You may find the worked example at the end of Section 8.4.2 helpful as you do the calculation below. We will use the equation from above, setting $k=6$, to relate the cluster's velocity dispersion to its mass.

$$M=6\frac{\langle v^2\rangle r}{G}$$

Astronomers have measured the Coma cluster's velocity dispersion to be about 1000 km/s within a radius of about 3000 kpc.

Questions

As we can see from the numerical activity above, only a fraction of the Coma cluster's mass is comprised of galaxies. This suggests that the Coma cluster contains dark matter. Where is the dark matter located? Well, remember that there is dark matter within galaxies themselves. Galaxies like the Milky Way are composed of 90-95% dark matter. There is also evidence for dark matter between the galaxies in the Coma cluster. In fact, astronomers estimate that the Coma cluster is about 90% dark matter in total (see more on this in Going Further 8.3: What's Between the Coma Cluster's Galaxies?).

Going Further 8.3: What is Between the Coma Cluster's Galaxies?

Is dark matter the only stuff between the galaxies in the Coma Cluster? In fact, it is not. With the advent of space-based observatories sensitive to the x-ray emissions from hot gas, an additional method of measuring the mass of galaxy clusters became available. x-ray observations showed that galaxy clusters contain a tremendous amount of gas that lies outside and between the galaxies within a cluster. In fact, the mass of the hot gas is comparable to, or even in excess of, the mass of all the galaxies in the cluster combined. The gas is often referred to as the intra-cluster medium. It has a low density, but a very high temperature. As a result, it emits x-rays.

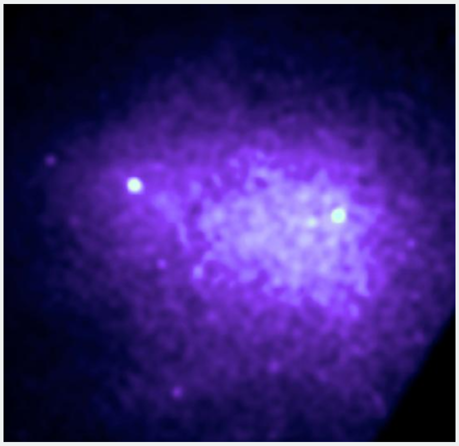

Figure B.8.2: The Coma Cluster in x-ray Wavelengths. This x-ray image from the Chandra Observatory shows the central 1.5 million light-years of the Coma Cluster. The blue haze represents a vast 100-million-degree-Celsius gas cloud which envelops the galaxies in the cluster. Compare this to Figure 8.19, which shows the Hubble Space Telescope visible light image of the cluster. Credit: NASA/CXC/SAO/A.Vikhlinin et al.

The temperature of a gas is related to the average speed of the gas particles, and the higher the temperature, the faster the particles are moving. This is because temperature is a measure of the average kinetic energy of the gas particles. The expression for kinetic energy is ½mv^2 for a particle of mass m and velocity v. So, using the temperature of the gas, we can calculate a velocity measurement for the gas. The velocity of the gas particles is determined by the gravity of the cluster—remember that if the velocity of the gas particles was too high, they would fly out of the cluster. So the cluster must be massive enough and have enough gravity to hold onto the gas. We can use the velocity measurement of the particles in the gas to determine the galaxy cluster's mass. This method is similar to using stellar motions or galaxy motions to determine mass.

Astronomers have found that the mass of the luminous, or light-emitting, matter from the galaxies in the cluster and from the gas in between the galaxies makes up only about 10% of the cluster's total mass. The Coma Cluster contains about 90% dark matter!

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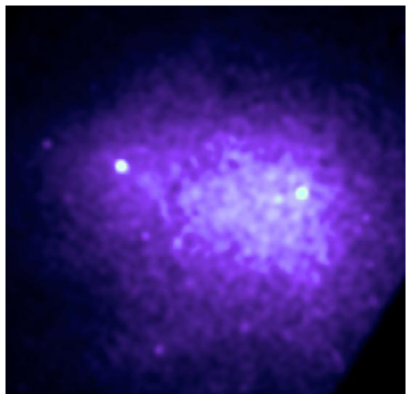

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The temperature of a gas is related to the average speed of the gas particles, and the higher the temperature, the faster the particles are moving. This is because temperature is a measure of the average kinetic energy of the gas particles. The expression for kinetic energy involved both speed and mass.

$$KE = \frac{1}{2}mv^2$$

This is the energy for a particle with mass m and velocity (or speed) v. So, using the temperature of the gas, we can calculate a velocity measurement for the gas. The velocity of the gas particles is determined by the gravity of the cluster—remember that if the velocity of the gas particles was too high, they would fly out of the cluster. So the cluster must be massive enough and have enough gravity to hold onto the gas. If that was not the case, the gas should have long ago dissipated.

So this means that we can use the velocity measurement (the temperature) of the particles in the gas to determine the galaxy cluster 's mass. This method is similar to using stellar motions or galaxy motions to determine mass. In this case, though, we are using the velocities of the particles (protons and electrons) that constitute the bulk of the hot gas.

Astronomers have found that the mass of the luminous, or light-emitting, matter from the galaxies in the cluster and from the gas in between the galaxies makes up only about 10% of the cluster's total mass. The Coma Cluster, like other galaxy clusters, contains about 90% dark matter!

This chapter has given the basic observational evidence for dark matter. The evidence is indirect, but still compelling. Additional evidence will be covered in a chapter on gravitational lenses. There is also indirect evidence for the existence of dark matter that comes from the formation of large scale structure. For the remainder of this chapter we will consider some of the possible forms the dark matter might be expected to take. We will also briefly look at alternative explanations of these observations.