14.2: The Formation of Galaxy Clusters and Groups

Learning Objectives

- You will understand that galaxy clusters are composed of galaxies, hot gas, and dark matter
- You will understand how galaxy clusters form from the hierarchical merging of smaller structures

What Do You Think: Which Came First?

14.2.1: Observations of Basic Cluster Properties

Clusters of galaxies are the largest gravitationally bound structures. They contain hundreds to thousands of galaxies that can be seen with optical telescopes. They also contain hot gas between the galaxies (30–100 million K) that can be seen with x-ray telescopes. We also know that galaxy clusters contain exotic (cold) dark matter. The mass in stars makes up about 1–2% of the cluster mass, the hot gas makes up about 5–15%, and dark matter makes up the rest (up to 85%). In other words, the mass of the gas between galaxies is about 6 times more than the mass of the stars in the galaxies and the mass of the dark matter is in turn about 8 times more than that of the gas. Galaxy clusters range in mass from a little more than 10^{13} to 10^{15} solar masses, and typical sizes are from 3–30 million light-years. Figure 14.10 is a composite image of the cluster Abell 1689 in optical and x-ray light.

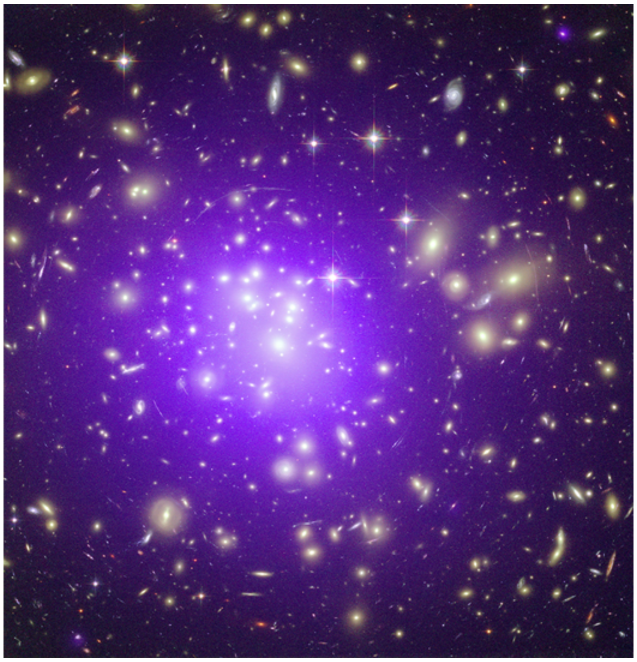


Figure 14.10: This composite image shows the galaxy cluster Abell 1689 in x-ray (purple) and optical (yellow, white, red) light. Hot x-ray gas in between individual galaxies contains more mass than all of the stars in the galaxies combined. The effect of gravitational lensing due to the total cluster mass (stars, gas, and dark matter) can be seen as arcs in the image. Credit: X-ray: NASA/CXC/MIT/E-H. Peng et al.; Optical: NASA/STScI

In many clusters, the gas and galaxies have settled into the same general area as the dark matter, a result of gravitational interactions. In some clusters, however, mergers are ongoing. In those systems the stars and gas have not yet settled into the dark matter potential well. One example is the Bullet cluster, shown in Figure 14.11. Two clusters have passed through each other. The system provides one of the few opportunities to study how exotic cold dark matter and normal baryonic matter behave differently in dynamical situations.

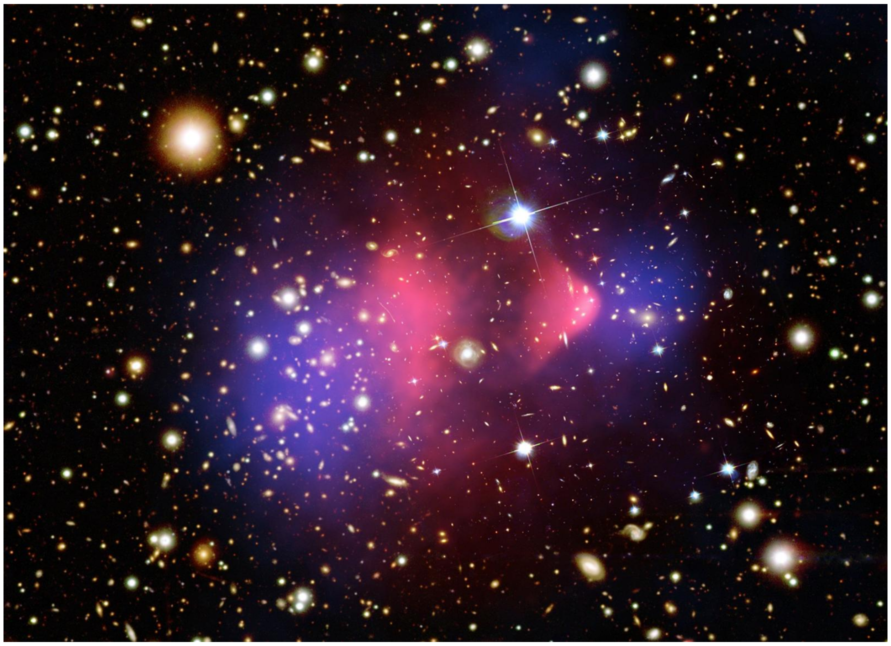


Figure 14.11: A composite image of the Bullet cluster. In addition to galaxies, which are seen in optical light, we see hot x-ray gas, here shown in pink. The blue areas are regions of dark matter, as determined from gravitational lensing. This is actually the result of two clusters that collided with each other. They are a distance of 3.4 billion light-years away from Earth and about 2 million light-years apart from each other. The gas, which is made of regular matter, has clumped in the middle; a shock front (shaped like an arrowhead) can be seen on the right. In contrast, the dark matter, which is collisionless, has passed through, and can be seen on the edges. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Lensing Map: NASA/STScI, ESO WFI, Magellan/U.Arizona/ D. Clowe et al.; Optical Image: NASA/STScI, Magellan/U.Arizona/D. Clowe et al.

Exotic cold dark matter particles are collisionless, which means they can move past each other without interacting strongly. Gas particles, which are made of regular matter on the other hand, interact very strongly via the electromagnetic force. They can produce shock waves. In the Bullet cluster, we see clearly that the dark matter in the two clusters (displayed in blue) has passed through the collision, ending up on the edges. The gas, on the other hand, has interacted through the collision and has ended up in the center. This distribution is well explained by dark matter and cannot easily be explained by alternative theories of gravity.

14.2.2: Modeling the Formation of Galaxy Groups and Clusters

One aspect of clusters that can be modeled with simulations is whether clusters formed from the mergers of smaller structures or from larger structures breaking apart. In a bottom-up structure formation scenario, small structures formed first and stuck together to form bigger structures. In a top-down scenario, bigger structures formed first and broke into smaller pieces. Simulations show that the formation of structures proceeded in a bottom-up manner—that small structures formed first and gathered together to build small galaxies, then larger galaxies, then clusters of galaxies. In fact, observations show that while galaxies themselves are mainly finished forming today, many clusters and super-clusters are still assembling.

In Animated Figure 14.12 we zoom in on a computer simulation from large-scale structures to galaxy scales. In Figure 14.13 we see a simulation of the formation of a group of galaxies similar to the Local Group, in which the Milky Way is located. In Animated Figure 14.14 we see a computer simulation. It starts with a nearly uniform volume of gas around 13.7 billion years ago. It then evolves to form a cluster and ends at present day with a massive central galaxy similar to the Milky Way. In all of these simulations, galaxies, composed of gas, stars, and dark matter, are colliding and forming as part of the cosmic web. This is hierarchical structure formation in action.

Video

Animated Figure 14.12: This movie of the Millennium Simulation zooms in from the largest scales to galaxy scales. Credit: Millennium Simulation

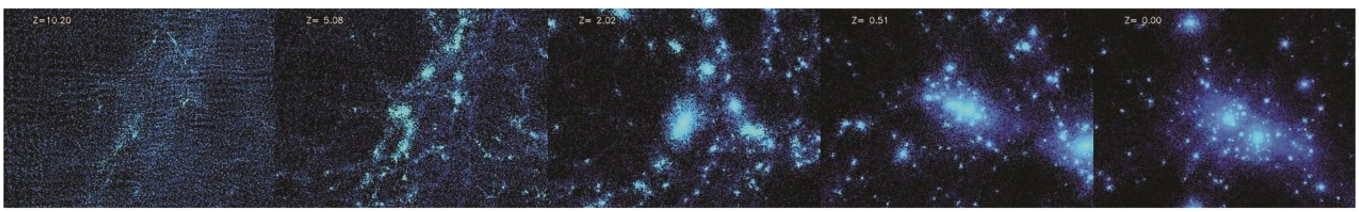
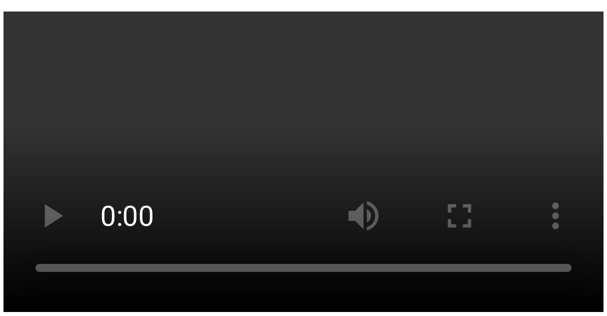


Figure 14.13: Simulation of the formation of a group of galaxies, from $z = 30$ to today. Earlier times are on the left and later times are on the right. Smaller structures form first and merge to form larger structures, beginning in earnest around a redshift of 5. The box size for this simulation is 14 light-years, in co-moving coordinates. Credit: Simulations were performed at the National Center for Supercomputer Applications (NCSA) by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.



Animated Figure 14.14: This simulation shows the hierarchical formation of structure within the cosmic web. Here we see smaller galaxies merging to form larger galaxies and a galaxy cluster. Credit: NASA/Goddard Space Flight Center and the Advanced Visualization Laboratory at the National Center for Supercomputing Applications (NCSA)

In all of these simulations, smaller structures form first and merge to assemble larger structures in a bottom-up scenario. Again, matter becomes more densely clumped over time. Dark matter provides most of the mass, and baryonic matter is attracted to it via gravity. Dark matter dominates the gravitational mergers and accretion, providing the backbone of the structure. Much of the gas is heated to x-ray temperatures by compression and shocks during the gravitational collapse. Stars form from cooler gas, eventually going supernova and injecting energy into the cluster. The gas also feeds active galactic nuclei in the centers of the largest galaxies of the cluster.

Galaxy clusters are interesting objects because they are large enough to be of cosmological importance, yet detailed astrophysics must be used to model them accurately. Simulations of their formation have been extremely successful at reproducing their observed properties, but there is still work to be done to fully understand their inner cores.
