Formation and Evolution of Galaxy Clusters in Cold Dark Matter Cosmologies
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Early civilizations have been wondering where everything came from and how everything began. For centuries, humanity has been wondering what our place in the vast world surrounding us is. Tied in with this was the fundamental question of how the world came into being. Early civilizations had a mythical view of the cosmos. For example, the Mesopotamian civilizations of Sumer and Babylon had a cosmology in which Earth was a disk surrounded by the underground waters of the Apsu and the underworld of the dead, with the heavens of the stars surrounding it all. Despite the highly sophisticated level of astronomy in the neo-Babylonian world and its inheritants, it is with the ancient Greeks that astronomy and cosmology entered the level of scientific inquiry. Building upon the observations carefully obtained and archived by the Babylonians, the Hellenistic Greeks were the first to use their geometric models to predict the observational reality, creating a quantitative as well as a qualitative model of the Universe. Eratosthenes measured the circumference of Earth, while Aristarchus measured size and distance of Earth and Moon. He even forwarded the suggestion that the Sun was at the center of our world, a view which only became the accepted view with Copernicus and Galilei in the 15th and 16th century.

It is with the Scientific Revolution of the 16th and 17th century that a truly scientific model of the Universe came into being. With Nicolai Copernicus in 1543 Earth finally lost its privileged central position in the cosmos. Standing on the shoulders of Copernicus, Brahe, Kepler and Galilei, it was Isaac Newton who managed to frame the laws of gravity and mechanics. This formed the foundations of classical physics. His view of a static space-time and a gravitational force resulting from action at distance made it impossible to open the view on the dynamic cosmological world view which we presently hold. It was Einstein’s General Theory of Relativity that formed the final breakthrough towards turning cosmology into a scientific inquiry. His metric theory of gravity turned space-time into a dynamic medium in which gravity is a manifestation of the curvature of space-time. Soon it was realized that this implies that the Universe could not be static and instead should be expanding or contracting. Friedmann and Lemaître were the first who worked out the expanding solutions for a homogeneous and isotropic Universe. Their theoretical ideas were soon confirmed in the seminal discovery in 1929 by Edwin Hubble of the expanding system of galaxies around us. His “Hubble Law”, describing the fact that distant galaxies are receding with velocities proportional to their distance, is still the fundamental basis for present day cosmology.

**Big Bang Theory and Inflation**

It was Lemaître who realized the tremendous implications of this finding. At earlier times, the Universe would have been a lot smaller, a lot denser and much hotter than the present Universe. This gave rise to the Big Bang Theory, stating the fact that the Universe came into being at some finite point in the past. We now know that the cosmos came into being 13.7 billion years ago in a seething sea of radiation and matter. Even despite its tremendous successes, the standard Big Bang theory does not explain the origin of structure of the Universe. This may be solved if the Universe underwent an inflationary exponential expansion phase. During this cosmic inflation, $10^{-34}$ seconds after the Big Bang, the
Universe blew up by a factor of $10^{60}$.

Inflation can account for the flatness of the Universe, the uniformity of its radiation and the origin of the primeval matter inhomogeneity. These inhomogeneities (initially in subatomic scales) were the seeds from which stars, galaxies and cluster of galaxies formed.

Figure 1 — The Big Bang theory. An schematic picture of the history of the Universe since the Big Bang. Cosmic timeline from M. Norman.

**Cosmic Microwave Background**

When structures started to form, matter and radiation were coupled. The Universe was dark as a consequence of the tight interaction between photons and baryons. This state lasted 379 000 years. It ended when the temperature of the Universe was cold low enough so as to allow the creation of stable atoms. The Universe had cooled down to 3000 K. In this moment, the Universe became transparent and the photons could travel freely through the Universe. This photons can still be observed today, as a radiation that occupies the entire Universe. This is known as the Cosmic Microwave Background (CMB) radiation. Its spectrum is that of a blackbody, with a temperature of $T = 2.755$ K. The CMB is one of the most important evidences of the Big Bang.

**Dark Matter**

When the Universe was $\sim 1/1090$ of its actual size, matter started to dominate the dynamics of the Universe. The gravitational influence of a mysterious dark matter component is responsible for the formation of structures we see today. This rare form of matter is insensitive to the electromagnetic force, making it invisible and, therefore, very difficult to study. It is thought to represent more than 85% of matter in the Universe. This large presence is one of the major challenges for present day cosmology.

**Dark Energy**

Even more mysterious is the presence of another kind of energy, the dark energy. All we can say is that dark energy has a repulsive gravitational force. Observations indicate that it represents nearly 73% of the Universe’s energy. It is responsible for the accelerated expansion of the Universe and assures its flat geometry. Observations also tend to indicate that dark energy is in the form of a cosmological constant, which appeared in Einstein’s Relativity Theory. When the cosmological constant takes over on the evolution of the Universe, which happened at a redshift of $z \sim 0.7$, growth of structure freezes.
Large Scale Structure of the Universe

The pure Big Bang theory answers the question of the origin of the Universe, but it does not provide us with an answer of how the structures that we see today formed. The growth of structures is the result of the gravitational growth of tiny primordial fluctuations (appeared immediately after inflation) in the primordial Universe. A given fluctuation whose density is higher than its surrounding will collapse. Small clumps of matter gradually merge and accrete while assembling into ever larger structures. Small subgalactic objects are the first to form in the Universe. They decouple from the expansion of the Universe and collapse. These small objects then merge and give birth to galaxies. The process continues, leading to the assembly of galaxy-sized halos into clusters of galaxies. Within this hierarchical evolution, galaxy cluster stand out as the most massive and most recently collapse objects in the Universe. Most find themselves at the moment in a state of relaxation and virialization. Their collapse time is comparable to the age of the Universe. These properties make galaxy clusters indispensable laboratories for the study of the evolution and formation of the Universe.

Galaxy Clusters

Galaxy clusters are the largest stable structures in the Universe. Typical properties of galaxy clusters include:

- They contain 50 to 1000 galaxies, hot gas and large amounts of dark matter.
- They have total masses of $\sim 10^{14} - 10^{15} h^{-1} M_\odot$.  
- Their radius are in the order of $\sim 2-6 h^{-1} \text{Mpc}^2$.
- Galaxy members have velocity dispersions in the order of $\sim 800-1000 \text{ km/s}$.

Galaxy clusters have been key astrophysical objects in the development of our current understanding of the large scale Universe. It was in galaxy clusters that dark matter was first detected. Clusters are also very luminous X-ray sources, emitted by a tenuous extremely hot intracluster gas with a temperature of $T \sim 10^7 - 10^8 \text{ K}$. The fact that they contain an atypical mixture of galaxies makes them into important probes of the study of galaxy evolution.

When observed visually, cluster of galaxies appear to be collections of galaxies held together by mutual gravitational attraction. However, their velocities are too large for them to remain gravitationally bound by their mutual attraction. This implies that there must be an additional invisible mass component or an additional attractive force besides gravity. Most of the mass of galaxy clusters is in the form of hot gas, which emits in X-ray. In a typical cluster perhaps only $\sim 5\%$ of the total mass is in the form of galaxies, $\sim 10\%$ in the form of hot X-ray emitting gas and the rest is in the form of dark matter.

Because galaxy clusters are on the best studied and understood objects in our cosmos, we may wonder whether we can find a trace of the cosmic dominant dark energy. This is the primary goal of this thesis.

In this thesis

In this thesis we have investigated the influence of dark energy on the formation and evolution of cluster of galaxies in several cold dark matter (CDM) Universes. We have shown that there is a negligible impact of a positive cosmological constant on several global and individual properties that marks the life of a galaxy cluster. There is, however, a considerable influence of the content of matter in the Universe on the evolution of cluster of galaxies.

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1. $1M_\odot = 1.989 \times 10^{30} \text{ kg}$, is the mass of the Sun.
2. 1 Mpc$=3.086 \times 10^{22} \text{ mts}$. 

Cosmological simulations and mass functions

In Chapter 2 we have extensively described the cosmological simulations we used throughout this thesis. These numerical simulations include six open Universes, four flat models and three closed cosmologies, with or without a cosmological constant. Each simulation consists of $256^3$ dark matter particles in a box of size $200h^{-1}\text{Mpc}$ with periodic boundary conditions. Every simulation has the same Hubble parameter, $h = 0.7$, and the same normalization of the power spectrum. The simulations were started at a redshift of $z = 49$, and run until the present cosmic epoch.

In order to facilitate comparison between each of the simulations in the various cosmologies, the primordial Gaussian density fields were assumed to have the same phases for each of the Fourier components. This ensures that we have the same large scale patterns in our complete set of simulations.

This property is seen in Fig. 2, where we show slices through the center of the box of three different models: $\Lambda\text{CDM}F_2$ (a flat model, top panel), $\Lambda\text{CDMO}2$ (an open model, middle panel) and $\Lambda\text{CDMC}2$ (a closed model, bottom). The patterns of the large scale structure are similar. The differences between themselves manifest in the different levels of clustering. The open, low matter density model contains less structure than the other ones. This is a result of the extremely low matter content in this cosmology. Possibly, in connection with the presence of a cosmological constant. As a result, growth of structure came to a halt at a significantly earlier epoch. This fact is strengthened in the zoom-in regions, where it is possible to see that Universes with high matter density have more evolved patterns, characterized by a higher level of clustering.

We have also investigated the mass function of objects in each of the simulations. The mass function is the number density of objects of a given mass. We find that mass functions do distinguish between the amount of matter in the Universe of the different cosmologies. However, at present epoch, we could not find any significant influence of the cosmological constant. We do find some noticeable effects at different redshifts. This is a result of the different dynamical timescales, a consequence of the different values of the cosmological constant.

Mass growth and virialization of galaxy clusters

In Chapter 3 we investigate the formation history and virialization of cluster halos. We first looked into the assembly history of a few identical clusters in three different time scales: redshift, lookback time and cosmic time. We found that nearly all differences have to be ascribed to the difference in matter density of the cosmological background. As with the mass function, the only noticeable influence of the cosmological constant is via its impact on the cosmic time.

An important characteristic in the evolution of galaxy cluster halos is their mass accretion history. We investigate this by looking into a few single cluster in various cosmologies and at the average in each of the simulated cosmologies. When looking at individual halos, we find that merging or accretion effects clearly influence the life of a halo. To some extent this seems to be regulated by the amount of matter present in each of the cosmologies. In those cosmologies where the matter content is low, most of the evolution takes place at early times, often accompanied by massive mergers at high redshifts. By contrast, on Universes with high matter content, such mergers are more frequent at recent epochs.

The spread around the average mass accretion history appears to be substantial. As a result, the corresponding band of mass accretion history in one cosmology tends to overlap with several others. This will make rather difficult to draw any conclusions on subtle cosmological effects such that of the cosmological constant.

We also study the virialization of dark matter halos, and in particular galaxy cluster halos. At present cosmic epoch, it appears that the halo population in every cosmology is close to a virial state. However, they do not attain the perfect virial relation for spherical matter clouds. While low mass halos show a large spread, cluster halos (high mass halos) are perhaps the most well-behaved halos. Nearly all of them obey the same virial relation, independent of cosmology. The only noticeable influence of cosmological background is through the spread around the virial relation. In Universes with high
Figure 2 — Three different cosmological simulations: ΛCDMF2 (top), ΛCDMO2 (center) and ΛCDMC2 (bottom). On the right, the zoomed-in region depicted on the left.
matter content it is larger than in low matter content.

**Physical characteristics of galaxy clusters**

In Chapter 4 we turned to the internal physical properties of galaxy clusters. We explore the influence of a positive cosmological constant on the internal mass distribution, the shape and morphology, and the angular momentum. The internal mass distribution is characterized by the density profile of the halo sample. We find that these density profiles have the same appearance in each of the simulated Universes. We do find, however, that halos in high matter density Universes are more concentrated. There is no clear indication for a dependence of halo concentration on cosmological constant. Regarding the morphology, we found that halos in every cosmology have a triaxial shape tending towards prolate. When studying the sphericity of halos as a function of mass, we find that halos in high density Universes tend to be less spherical. Finally, we find that the angular momentum of halos increases steadily, intimately related to the increasing mass of halos.

**Scaling relations**

The structure and dynamics of (near) virialized objects like cluster of galaxies translate into some profound scaling relations between the mass, size and kinematics (velocity dispersion) of these objects. In Chapter 5 we investigate the Kormendy, the Faber-Jackson and Fundamental Plane relations between the mass, radius and velocity dispersion of cluster sized halos. Although these relations were first related to elliptical galaxies, Schaeffer et al. (1993) found that they also relate to galaxy clusters. In each of the simulated cosmologies we recover the Kormendy, Faber-Jackson and Fundamental Plane relation. We find that the Kormendy and Faber-Jackson relation are mildly sensitive to the density matter of the Universe rather to the cosmological constant. The largest impact of the matter density is on the width of the Fundamental Plane: it is almost directly proportional to the matter density of the Universe. We find that this width is a reflection of the virial state of cluster halos. The evolution of the Kormendy and Faber-Jackson relation is an indication as to where in the Fundamental Plane cluster halos lie.

**Future evolution of the Universe**

$N$-body simulations have become a necessary tool for the investigation of the evolution of structures in the Universe. They represent realistic descriptions of the formation and evolution of structure formation in the Universe. They also allow us to to investigate the influence of the cosmological constant on the future evolution of structures in the Universe. In Chapter 6 we look into the future evolution of galaxy clusters. In Fig. 3 we see how an object in an expanding Universe will look like. In the top panels, we see the evolution in comoving coordinates, while in the lower panels the evolution is seen in physical coordinates. In physical coordinates, the size of the object is almost the same throughout its history, while in comoving coordinates it shrinks, to the point it is almost invisible, due to the expansion of the Universe. We find that in the near future, the mass function of objects (number density of objects of a given mass) freezes: there is no growth of structure. As a consequence of this, there is hardly any differences between the mass accretion history of halos in any given cosmology. As halos evolve towards the future, they become more and more spherical in shape, achieving a nearly perfect spherical morphology in the far future. Given that halos hardly gain mass in their evolution towards the future, the angular momentum remains almost constant. They also reach a high degree of virialization. This is also reflected on the scaling relations, which we found to be much tighter that at present time. The width of the Fundamental Plane is thinner than at present cosmic epoch, and is nearly the same for every cosmology. This is an indication that galaxy cluster halos have had enough time to virialize and reach dynamical equilibrium. These findings tell us that in the far future it will be difficult to identify in which Universe we live in.
Figure 3 — Evolution of a single cluster in a flat Universe towards the future. Top panels: evolution in comoving coordinates. Lower panels: evolution in physical coordinates. We see how in comoving coordinates, as a consequence of the expansion of the Universe, starts to grow in isolation.

Supercluster of galaxies

Identifying supercluster of galaxies is a very difficult task. As they are the largest structures in the hierarchy of the Universe, they are just starting to form. We apply the criterion derived in Dünner et al. (2006), in which they are identified with gravitationally bound structures. We use this as a physical definition of supercluster of galaxies. We construct the mass function of this bound objects, and, assuming that superclusters are the most massive of this sample, we find that in a region of a volume comparable to the Local Universe the most massive supercluster would have a mass of $\sim 8 \times 10^{15} h^{-1} M_\odot$. This is slightly bigger than the mass derived for the Shapley Supercluster (the largest concentration of galaxies in the Local Universe) given in Dünner et al. (2008). We also find that in the Local Universe we would be able to find 2 superclusters that are similar in size and mass to the Shapley Supercluster. As for the morphology, we find that superclusters at present time contain a substantial amount of substructure, having a triaxial shape, tending towards prolate.

Final Conclusions

In this thesis we have investigated the influence of a cosmological constant in the formation and evolution of galaxy clusters. To this end, we used a wide set of cosmological simulations that included the three possible geometries of the Universe: open, flat and closed. Each of these simulations did or did not include a cosmological constant. In this way, we sought to learn more about the influence of the cosmological constant on the structure, dynamics and evolution of cluster of galaxies.

We have carried out several studies of global and individual physical properties of galaxy clusters. We conclude that the cosmological constant does not influence the formation and evolution of galaxy clusters. The only noticeable influence is on the cosmic time: it either stretches or compresses the available dynamical timescales for the cluster evolution.