Gas physics in simulated galaxy clusters

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English Summary

The universe is a vast and often incomprehensible place. There are nigh uncountable different objects, in a nigh immeasurably empty void, however, that emptiness is often an illusion. We, earthly beings, are prone to imagining that the space that surrounds us is all the universe has to offer. After all, looking up to the night sky, we see innumerable stars shining down at us. In reality, this is but a minute fraction of all the universe has on offer. The average Dutch night, infused with the stray light from cities, greenhouses and streets, reveals no more than 250 stars. A crystal clear night in the Dutch wilderness grants us 1500 at most. Even that is a small fraction of the 200 billion stars in the Milky Way. Apart from the fact that the Milky Way, our own galaxy, comprises over a hundred billion stars, there are an estimated 100 billion galaxies. Every one of those galaxies with its own hundred-billion star contingent. In short, what we, humans, can see is nowhere near an accurate representation of the universe.

Galaxies much like the Milky Way are spread through the universe as a spiderweb or mold culture, with long filaments straddling large voids coalescing at giant intersections. The most massive objects in the universe, clusters of galaxies, reside at these intersections. Counting up to thousands of member galaxies, they far exceed in size and mass the small group formed by the Milky Way and Andromeda galaxies. By virtue of the enormous gravity generated by these objects, the dilute gas inbetween galaxies is heated to millions of degrees. Such hot gas spontaneously emits X-ray radiation. Using satellites orbiting Earth, we can observe this radiation.

From an experimentalist's point of view, our Universe is disappointing in that there is only one. Large clusters of galaxies are naturally interesting to the inquisitive beings that are Astronomers. Unfortunately, they are extremely far away and their size makes them sluggish, dragging any process out to timescales far longer than the history of humanity. One solution is to recreate these clusters in a computer. This thesis is based on such computer simulations, which use large supercomputers, resulting in petabytes of data, and resulting in an impressive reproduction of our Universe. In this thesis use is made of simulations reproducing two important observables. First, the number of galaxies of a given size matches what is observed in the Universe. Second, the amount of gas in galaxy clusters is consistent with what X-ray observations tell us we find in real clusters. Using thesis simulations, this thesis studies a number of phenomena.

Spatial distribution of gas

Even if simulations reproduce properties of clusters as a whole, there is no guarantee that the distribution within a cluster is realistic. To make the comparison with reality easier, we imagine clusters to be perfect spheres. Just as for an onion, we imagine the cluster consists of layers from the inside out, and we measure values related to the gas physics in each such layer. Such measured results in layers are called "profiles". From a profile astronomers can quickly see if a simulated object adheres to reality.

Other astronomers, who spend their time doing observations, clearly distinguish two groups of objects from such profiles. Studying the temperature profiles, one group has a cold centre, whereas the other has much less of a temperature difference between the centre and outer regions. The common rationale is that the "cool-core" clusters have more high-density gas, enhancing the cooling rate. A litmus test for simulations is to reproduce this dichotomy.

Treacherous scales

Everyone having spent time on a scale will recognize the moment where you wonder if it is off today, or that 5 slices of cake truly is too many. Though physicists have developed highly precise scales, those are without any use in astronomy. The objects we hope to weigh are not only freely floating in the weightlessness of space, they are also too far away to ever get them anywhere near a scale. Different methods are needed. A nifty trick has been devised for galaxy clusters. Because of their size and sluggishness, we can assume them to be in equilibrium. This simplifying assumption allows us to calculate their total mass by only measuring the thermal pressure profile. Even though this method is fairly successful, biases in the acquired masses have become apparent. The simplifying assumption of equilibrium has erased important details, resulting in an underestimate of the total mass.

Using simulations, the different components of the mass estimate can be studied in detail, allowing for an assessment of the average deviation and relative import of the different factors at play. This knowledge can then be applied to observations, potentially improving future mass estimates.

This thesis

This thesis is based on cosmological and idealised simulations within the astronomical domain. First, different simulations methods are compared, after which the focus of the thesis shifts towards galaxy clusters within the FLAMINGO simulations. The clusters' profiles are compared with observations, mass estimates are critically assessed from a theoretical perspective, and finally we aim to understand the correlation between deviations from the mean in different physical quantities of the same cluster.

Chapter 2: The sensitivity of the results from simulations to different fluid dynamic simulation algorithms

Simulations of astrophysical fluids require translating fluid dynamic equations into a numerical language. This can be done in a number of different ways. Perhaps the most consequential choice is whether to divide space into fluid cells or represent it using particles. This chapter shows that these choices have a large influence on the final result of simulating the interaction between a dense cloud of gas and a dilute wind.

Chapter 3: A comparison of thermodynamic profiles between simulations and observations

The new FLAMINGO simulations are the largest hydrodynamic cosmological simulations of the Universe to date. As a result, there are more clusters of galaxies in these simulations than in any previous simulation. This chapter compares simulated cluster profiles with observations, elucidates the impact of cool-cores and illuminates the effect of changing simulation parameters related to black holes and stellar explosions.

Chapter 4: Weighing galaxy clusters

This chapter delves into measuring the mass of galaxy clusters in the FLAMINGO simulations, as is done using X-ray observations. We find that the mass is underestimated by 10-15%, however, the magnitude of the deviation is strongly dependent on the way black holes inject energy into the clusters. The second part of this chapter aims to understand the origin of these differences. For example, one of the findings is that the hot X-ray emitting gas in clusters is not actually in equilibrium, and its rotational motion is non-negligible.

Chapter 5: The origin of scatter in the X-ray luminosity – halo mass relation

Simulations know every single quantity for every single object, which is unlike observations of the real universe where some information is often missing. The abundance of data in simulations enables the research of why apparently similar clusters have very different X-ray luminosities. In this chapter we aim to disentangle all the different correlated quantities and find that a large part of the scatter remains unexplained, suggesting large amounts of intrinsic variation between clusters.