A Hydrodynamic Simulation of Cluster Formation

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Abstract

We have developed a hybrid cosmological code to probe the baryonic gas dynamics of large cosmological structures. An adiabatic simulation of large scale structure formation has been performed, using initial conditions specified by the cold dark matter (CDM) power spectrum normalized to the COBE detection. A baryon fraction of 0.06 is adopted and the simulation follows an $85h^{-1}$ Mpc box with 25 million zones and 3 million particles. Analysis of the resulting data provides a powerful diagnostic of this particular model. The method shows promise in general by removing another layer of uncertainty between theory and observation. To demonstrate this, we compute an X-ray luminosity function that is straightforward to compare with observations. We also investigate some astrophysics of cluster formation.

1. Introduction

Although relatively rare, the high X-ray brightness of the large clusters allows them to be seen for great distances and complete samples of relatively nearby clusters have been developed[9]. Previously, others have used the cold dark matter (CDM) prescription to make a quantitative prediction of cluster statistics expected from such a model[8,10]. These comparisons evolved only the dark, collisionless component, identifying galaxies with the centers of dark halos and comparing the derived clusters against optical compilations, such as Abell's catalog. There are, however, several steps in the analysis, such as identifying cluster characteristics (due to the absence of baryonic matter in the simulations) and comparison against optical observations (projection effects) which increase the uncertainty of the results. Here we model both the hot gas as well as the dark matter and compare the result against X-ray observations which are largely insensitive to projection effects.

The numerical method combines a particle-mesh code which models the dark matter as collisionless particles with a Eulerian grid-based solver for the hydrodynamics. This is based on the third order-accurate piecewise parabolic method[4]. We have implemented this scheme for cosmological systems and have developed a comprehensive test suite[3].

The results described below were computed with initial conditions described by a CDM power spectrum, normalized to COBE[6]. This implies that the variance of the mass overdensity within spheres of radius $8h^{-1}$ Mpc is $\sigma_8^2 = 1.1$. A periodic box with 270^3 zones and

Figure 1. The X-ray luminosity function integrated from 2-10 keV; the solid line indicates observations, while the dashed line corresponds to the simulated clusters. Uncertainties are statistical only.

3 million particles of physical size $L = 85h^{-1}$ Mpc with $h = 0.5$ was adopted, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. A flat universe with $\Omega = 1$ and baryon mass fraction of $\Omega_b = 0.06$ was chosen. The simulation was adiabatic; heating and cooling is due to gas dynamics, not radiative processes.

2. The Cluster X-ray Luminosity Function

To identify clusters, we compute the x-ray luminosity from thermal Bremsstrahlung (here integrated from 2-10 keV) for every zone in the simulation. Local maxima above a certain luminosity threshold ($L = 10^{38}$ erg s^{-1}) are found and labelled as clusters. The total luminosity of the cluster is determined by summing the contribution from neighbouring zones in a volume corresponding to a sphere of radius $1h^{-1}$ Mpc. We have also done this for $0.5h^{-1}$ Mpc spheres and looked at the results for a variety of redshifts[2]. Since the thermodynamic state of the gas is completely known, we can also analyze other cluster characteristics, but here we restrict ourselves to the better constrained total luminosity.

From this sample of clusters we can compute a luminosity function, shown in Figure 1. The highest luminosity cluster has about $L = 10^{45}$ erg s^{-1} and we expect that this is limited by the finite size of the volume computed. The lower luminosity clusters have larger systematic uncertainties as they are smaller and therefore modelled with fewer cells. The effect of our resolution limit is hard to gauge precisely, although resolution studies indicate that it is unlikely that we have underestimated the luminosity.

Also shown in the figure is the observed X-ray luminosity function from a sample observed with the HEAO-1, Ariel and Einstein experiments[5,9]. Although the slope is approximately correct, the predicted number density of large clusters is about five to ten times larger than observed. The curve in Figure 1 is reasonably well fit by a Schecter function, but with a slope flatter than observations indicate.

Figure 2. Observed temperature minimum in a simulated cluster (dashed line). To create this figure, we have binned neighbouring cells and computed a volume weighted average, showing one sigma confidence intervals. We also speculatively plot (solid line) the observed radial temperature distribution of the Coma cluster from Watt, et al. (1993).

3. Cluster Central Temperature Minima

In the process of modelling such a large volume of space we have a sizable catalog of simulated clusters. Although the resolution is marginable, we can trace the hydrodynamics of individual clusters. We have observed that some clusters, especially those that are the result of a small number of merging events, exhibit a temperature minimum near or at the central density maxima. Although this behaviour is not exhibited in the majority of clusters, it did occur with sufficient frequency to warrant investigation. It is worth restating that the phenomenon is due to the dynamics of shocks and cosmic expansion, not radiative cooling.

Figure 2 shows the radial temperature profile of a cluster typical of those showing such minima. We have computed the profile by dividing the cells into several radial bins and computing the average radius and temperature, weighting by volume. If the profile were continued beyond that shown, it would drop due to the presence of other sub-clusters and cold gas.

Although meaningful statistics about the relative frequency of the inversion is difficult to determine because it is almost entirely absent in small clusters, which is almost surely to do with the lack of computational resolution, it is clear that less than ten percent of large clusters exhibit this behaviour. However, a visual inspection shows many large temperature inversions which are either distorted or do not lie at the density maxima and hence are not detected by the simple method described above. Inspection of the time evolution of a number of clusters shows that one or more of the components of the cluster form with a central dip but they are effectively erased by merging. This may imply that the presence of a minimum indicates a cluster that either formed from one large non-linear wave or has not been completely mixed. The principles active here are insensitive to the precise nature

of the initial conditions and are more a result of hydrodynamics plus hierarchical clustering (which is observed in a wide range of models). We note that linear analytic calculations[7] have lead to a similar conclusion.

We mention two possible observations of temperature depressions in the centers of real clusters. The ROSAT observations of M87[1] show a decline from 6 keV to about 2 keV over a similar range of distance as in Figure 2, and a smaller decline is seen in the spacelab observations of the Coma cluster[11] Both must be regarded as tentative identifications as isothermal distributions are formally within the uncertainties. Also, the presence of a cooling flow in M87 complicates the interpretation.

4. Conclusions

Although much can be learned from collisionless simulations and self-similarity calculations, the use of hydrodynamics to resolve the non-linear evolution of the gas is not just useful, but necessary as we probe smaller and smaller scales where the gas dynamics become dynamically more and more important. There are also a number of unanswered questions about the evolution of clusters which require more input physics, such as the source of metallicity and the possible presence of magnetic fields.

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