Properties of Merging and Relaxed Clusters from Hydrodynamical Simulations

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Galaxy clusters are the biggest objects in the universe, with sizes up to 10 million light years in diameter, and weighing ~10^{14}−10^{15} solar masses. They can be observed in the optical (as a local clustering of visible galaxies), the X–ray (thermal emission from hot ionized gas in the potential well of the cluster), and in the microwave band via the SZ effect. Cosmological studies of galaxy clusters have played an important role in establishing the "standard" cosmological model. For example, from the early 1990s these studies have been consistently pointing to a low-matter content in the universe–a finding confirmed by breakthrough studies of the Hubble diagram from distant type Ia supernovae, made about a decade ago. Even a small sample of ~100 clusters in the redshift range z =0−0.8 from the old ROSAT X–ray survey is enough to convincingly demonstrate the presence of dark energy that accelerates the expansion of the universe, and slows its growth of structure [1].

The reason galaxy clusters are such an important cosmological probe is that they are the most recently formed objects, as well as the most massive virialized structures, in the universe. Since clusters form over a time scale comparable to the age of the universe, their number density is strongly affected by the rate of the growth of structure of the universe. Also, due to their recent origin, clusters form in the epoch when dark energy starts to dominate the content of the universe, making them exponentially sensitive to the amount and properties of dark energy. An additional importance of cluster cosmology is that measurements of how structure grows (driven by gravity), together with independent measurements of how the universe expands (Hubble parameter), are a direct test of the theory of general relativity on the largest accessible scales.

The scientific community and sponsoring agencies have recognized the importance of conducting precise surveys of galaxy clusters—two Sunyaev-Zel'dovich effect (SZ, inverse Compton scattering of microwave radiation on free electrons in intracluster gas) surveys (South Pole Telescope and Atacama Cosmology Telescope) are already collecting data. Their optical/near infrared follow–ups consist of the ongoing VISTA survey, the Dark Energy Survey (start scheduled for 2011), and the Large Synoptic Survey Telescope (towards the end of this decade).

Finally, the X–ray satellite eROSITA is due to fly in 2012; one its components is a full-sky survey, with about a 100 times lower flux limit than the ROSAT survey. A major roadblock for all of these observational campaigns is measuring cluster masses–a notoriously difficult problem in astronomy–directly possible only for small sets of clusters through gravitational lensing. For all others, we have to use different observables (e.g., X–ray luminosity, temperature, galaxy velocity dispersion, galaxy richness) and relate them to the mass.

In our previous work [2], we have found that the fraction of merging clusters and groups of galaxies can in itself be a probe of cosmology. This is an interesting angle to probing cosmological parameters, as it does not have the same systematic problems as the cluster mass function (for example, the sample completeness problem is practically eliminated). While the method alone does not have the discriminating power that the mass function has, it can serve as an improvement to the accuracy of cluster probes and, in particular, as a cross-check of a survey's systematic errors. However, in order for the method to be implemented in practice, there has to be a more observationally motivated criterion to classify clusters as relaxed or merging.

The first aim of our project is to find such an observational criterion. In order to do so, we are using hydrodynamical simulations of a cosmological volume (500 Mpc on the side, for details see [3]) containing ~4500 galaxy groups and clusters at z = 0, with mass greater than 5×10^{13} solar masses. For these simulated objects we can reproduce their projected observable properties, but we also know their 3D gas properties, as well as the distribution of (dominant by mass) dark matter. A morphological investigation can straightforwardly tell us if a cluster is relaxed or merging; however, it is impractical for two reasons: (1) the observer rarely has information on the distribution of dark matter, and (2) upcoming surveys will map large numbers of clusters–up to 10^5 . We have developed a method based on the

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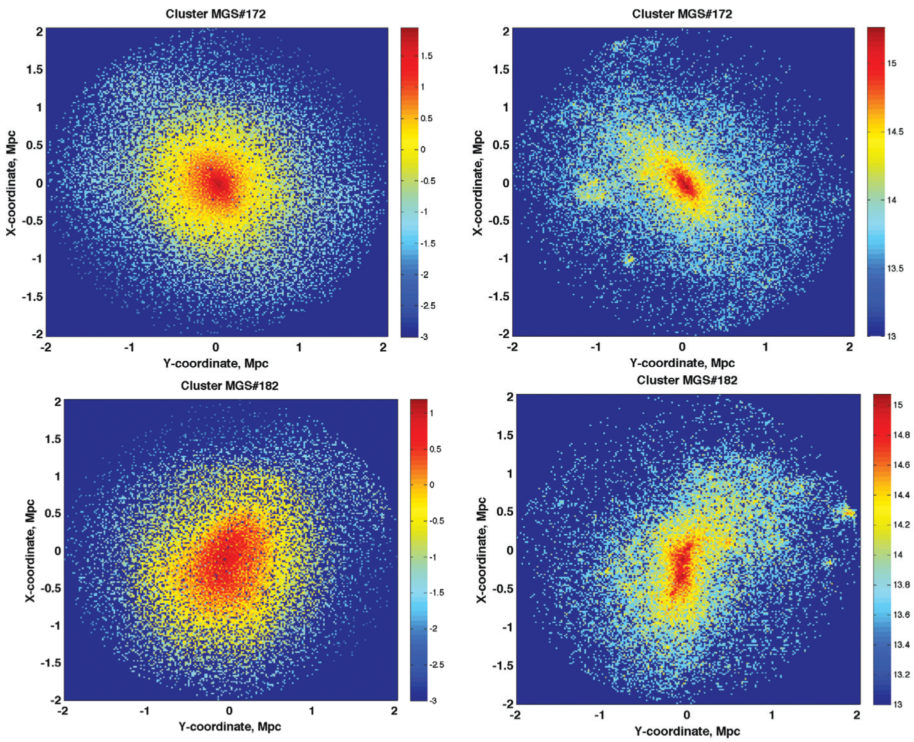

Fig. 1. Example galaxy clusters in hydrodynamical simulations: relaxed (upper row), and merging (bottom row). On the left we show the observable quantity–projected X-ray luminosity of the intracluter gas, on the right is plotted the distribution of dark matter that is inaccessible to observations, but dynamically dominant.

distribution of X–ray luminosity, and have used a smaller sample of a few hundred clusters as a test set, to confirm that our method agrees with morphological selection.

The second aim of our project is to improve cluster mass proxies. Scaling relations between direct observables and cluster masses can commonly be described as power laws with a scatter of ~15–30%, depending on the observable (smaller scatter is for SZ, larger for the X-ray observables). Having developed a prescription on how the observer can classify clusters into two groups, we can determine the mean and the scatter of scaling relations for each class separately. It turns out that the relaxed sample, which contains most of the clusters, has a different mean, but more importantly, it has a narrower scatter in the scaling relations.

Our current analysis is being done on clusters at redshift $z = 0$; we are now extending our work to earlier epochs, covering the completely relevant redshift range ($z \leq 2$).

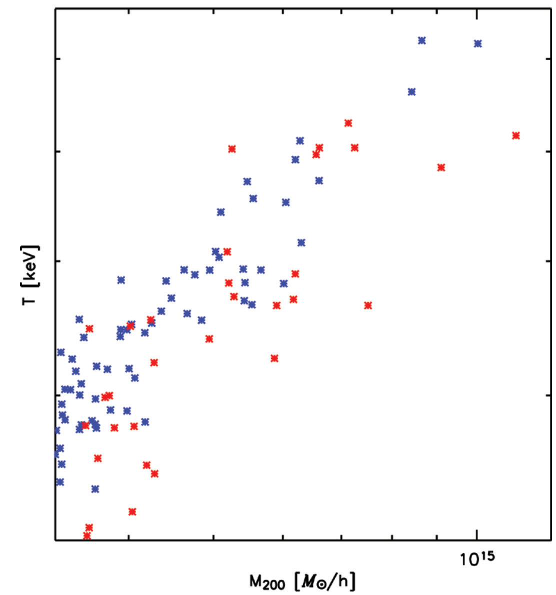

Fig. 2. Spectroscopic temperature–cluster mass relation. Blue points are clusters identified as relaxed, red points are clusters which have recently undergone a major merger. Notice that merging clusters bias the whole sample low and increase the scatter in the T-M relation. The same trend exists in the X-ray luminosity–mass relation.

[1] Vikhlinin, A., et al., *Astrophys J* **692,** 1060 (2009).
[2] Lukić, Z., et al., *Astrophys J* **692,** 217 (2009).
[3] Stanek, R., et al., *Astrophys J* **715,** 1508 (2010).

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