Galaxy Cluster Astrophysics and Cosmology: Questions and Opportunities for the Coming Decade

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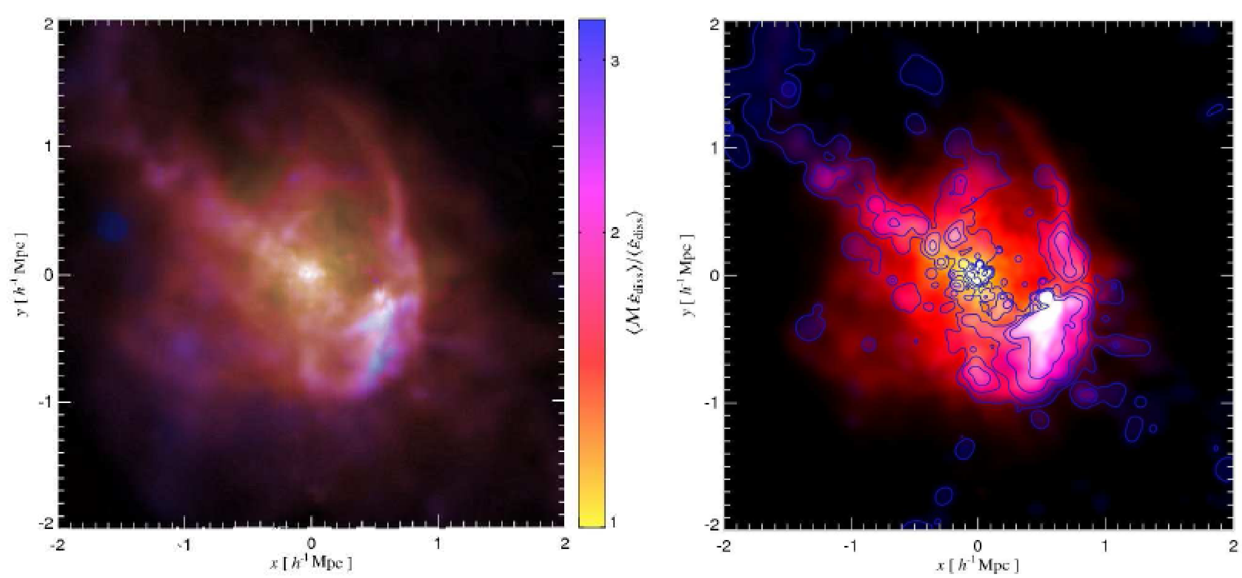

Simulated cluster shocks with Mach numbers (L) and 150MHz emission (R). Fig 1 from Battaglia et al. (2008).

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1 Motivation and questions

Clusters of galaxies provide us the opportunity to study an "ecosystem" — a volume that is a high-density microcosm of the rest of the Universe. Clusters are signposts for early structure formation, and are moderately isolated, growing on the Hubble timescale from the Cosmic Web. Clusters are excellent laboratories for studying plasma physical processes as well as for studying how super-massive black holes interact with the ambient cluster plasma. The next generation of cluster surveys is well suited to address fundamental problems in physics and cosmology (e.g. [1]), such as further constraining the Dark Energy equation of state [2] or to test whether our understanding of gravity is complete. Time is ripe to tackle the following important questions with clusters on an individual basis or as an entire population using multi-wavelength observational campaigns:

- **How do clusters form and grow?** How does feedback from star, galaxy, and black hole formation impact cluster structure and evolution? What detailed physical processes govern the heating and cooling of cluster cores? Are clusters pre-heated before they are assembled? What are the robust mass observables and scaling relations that can be used for cosmology?
- **How do the cluster medium and its constituents evolve?** How much pressure is provided by the thermal plasma, by turbulence, and by the non-thermal particle populations? How are metals mixed into the medium? How does the hot ICM affect evolution of cluster galaxies and vice versa?
- **How do we use clusters of galaxies as a window on fundamental physics?** Does Dark Matter interact or is it collisionless? Does Dark Matter annihilate? How does Dark Energy affect the growth and evolution of clusters? Does Dark Energy only change the expansion history of the Universe or is our understanding of gravity on the largest scales of the Universe incomplete? Do exotica (cosmic strings) impact cluster and structure formation in any way?
- **What can we learn about plasma astrophysics in clusters?** What causes non-thermal high energy cluster emission in the radio and hard X-rays? What is the origin of large scale magnetic fields and how do they evolve? How do shocks of moderate strength accelerate relativistic particles? What are the properties of turbulence in the cluster medium, and how is this coupled to the cluster structure? Do anisotropic transport processes in the collisionless plasma play an important role?

These questions are closely interlinked and require a multifaceted approach bridging the observational and theoretical. Complementary to other approaches to measuring the expansion history of the Universe (e.g. SNeIa, BAO), future large surveys of galaxy clusters potentially provide a powerful probe for the growth of structure and hence are an invaluable tool for testing our understanding of General Relativity. This however is only possible if systematics associated with cluster mass calibrations, sample selection effects, and our

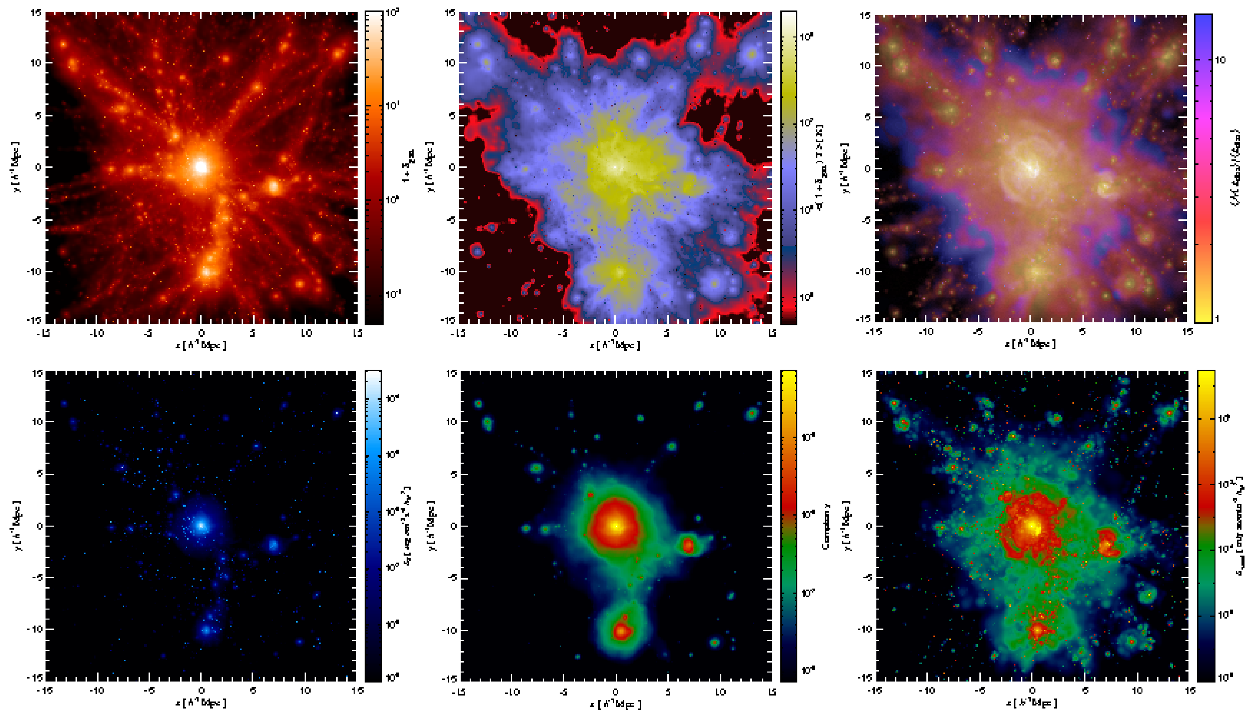

Figure 1: Simulated super-cluster region around a Coma-like cluster. *Top row L to R*: Projected gas density, mass-weighted temperature, and Mach number of formation shocks. *Bottom row L to R:* Associated observables X-ray surface brightness, amplitude of the SZ effect, and the radio synchrotron emission. Note that each of these observables is sensitive to different physical properties and combining different observables enables us to solve for the underlying physics. Taken from [3].

incomplete knowledge of the physics of the intracluster medium can be understood and controlled.

Clusters of galaxies provide unique opportunities for investigating non-equilibrium processes in plasma astrophysics. Combining cluster observables from the radio to Gamma-rays enables us to probe unique characteristics of the intracluster plasma. Conditions range from magnetically dominated regions within radio lobes to plasma dominated by thermal pressure, with bulk motions being subsonic within cooling cores to predominantly supersonic in the accretion regions. Hence, observationally and theoretically, we expect a complex interplay between cosmic rays, magnetic fields, and turbulence which poses a range of intriguing physical puzzles. There are many excellent recent papers on observational and theoretical aspects of cluster astrophysics and cosmology, e.g. [4].[1]

[1] In this white paper, unfortunately, we do not have the space to do proper justice to all the authors and papers on this subject, and only provide a few examples as references. We have also shown a modest bias towards papers and examples from the authors' work, and for highlighting the most recent results.

2 Cluster Astrophysics Now

In the past decade, great advances have been made in our understanding of clusters of galaxies, from the standpoint of their internal structure and evolution to their place in the larger scale structure of the Universe. These advances have been made possible by tremendous improvements in theoretical modeling and numerical simulation, as well as a wealth of new information provided by multi-wavelength surveys of the Universe. Below is a list of highlights that are jumping off points for future work:

Explosion of Cluster Observations: SDSS and other optical/IR galaxy surveys have yielded many new candidates. The ROSAT cluster surveys are still our best all-sky X-ray sample, and CHANDRA and XMM-NEWTON have provided spectacular detailed images and spectra. Progress is still being made in the use of these surveys for characterizing the growth and evolution of clusters through cosmic time. Future O/IR and X-ray surveys will greatly expand these classic cluster catalogs, while new samples will be obtained from the identification of clusters through the Sunyaev-Zel'dovich (SZ) effect using bolometer cameras on millimeter and submillimeter telescopes. A combined analysis of X-ray, Sunyaev-Zel'dovich, and weak-lensing data of a large cluster sample is needed to address possible biases, e.g. [5].

New Simulation Technology: There are a number of excellent and widely-used N-body and hydrodynamic simulation codes that have been developed throughout the past decade by the theoretical community (e.g. [6]). These, along with analytic and semi-analytic modeling, have ushered in a new era in our understanding of the astrophysics of clusters and large scale structure, as well as enabled us to feed simulated Universes into our designs for the next-generation of astronomical facilities. See Figure 1. Another example is the "Millennium Simulation"[2], one of many widely-used resources for astrophysics and cosmology. Extensive comparisons between codes have been carried out [7] to verify the validity of results.

Parameter Extraction: As simulations become increasingly realistic, they also become more complex, and defined by a larger number of physical and computational parameters. Determining these parameters by confronting a necessarily finite number of simulations with observational data will be a future challenge. Techniques for addressing this problem are being developed [8].

Evolution: Using cluster samples to study cosmology as well as the evolution of structure requires understanding the relation between the observables (X-ray luminosity, Compton-y, richness) and the actual masses and structure of the clusters. Current work has been focusing on calibration of scaling relations (e.g. [9]) but it will be an important task to push this to higher redshifts.

Internal Structure and Shocks: Sensitive X-ray observations of clusters using the new generation of space telescopes CHANDRA and XMM-NEWTON are extending our knowledge on the internal structure and hydrodynamical state. In turn, simulations are helping us understand how the intracluster medium depends on non-gravitational processes such as galaxy formation [10]. The observations have made it clear that spectacular shocks permeate the intergalactic medium. Simulations are able to connect this to the past history of the gas [11, 12]. Structure, such as the presence of a cooling core, depends upon merger history [13].

Non-thermal processes: In cluster cores, X-ray and radio observations show clear relations

[2] `http://www.mpa-garching.mpg.de/galform/millennium/`

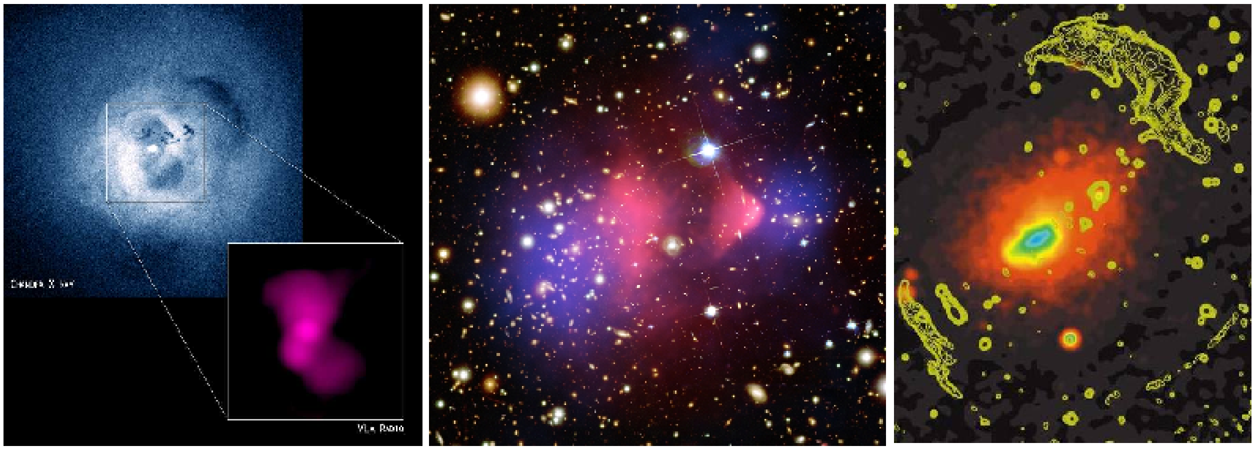

Figure 2: Cluster astrophysics at work! *Left:* The Chandra X-ray image of the Perseus cluster showing bubble and shock substructure. The VLA 90cm radio (inset) traces jets from the AGN filling the X-ray cavities [14]. *Center:* The "bullet" cluster experiences a major merger that causes the gas (X-ray in red) to lag behind the Dark Matter (weak lensing mass in blue) [15]. *Right:* Post-merging cluster A3667 (X-rays in color) with two giant radio synchrotron relics (contours) indicating the shock acceleration of electrons [16]. Parts of image composites courtesy Chandra image archive.

between X-ray substructure and radio emission from synchrotron-emitting particles injected by AGN [17, 18]. See Fig. 2. On large scales, some aspects of the diffuse non-thermal emission in the radio and hard X-rays are still not understood although considerable theoretical progress has been made by following cosmic ray particle injection and transport while predicting the associated non-thermal emission [3].

Magnetic Fields: The new generation of detailed hydrodynamic simulations are allowing us to start to model in detail the role of magnetic fields and particles in clusters both in the bulk of the intracluster medium as well as at interfaces of merging cores and rising AGN bubbles. This can be probed via sensitive low-frequency radio observations of the synchrotron emission, and measurements of the Faraday rotation [19]. See Figure 3. The challenges include modeling associated anisotropic transport processes of plasma particles that might govern the evolution of magnetic fields through instabilities, the uncertain topology of magnetic field structures, and the role of reconnection.

Sub-grid Physics: There are a number of small-scale "sub-grid" astrophysical processes that impact the larger-scale structure of clusters. In addition to the non-thermal physical effects noted above, star formation also affects clusters at some level through its feedback effect on galaxy formation. Simulations are still in the infant stages on modeling this, but progress is being made (e.g. [20]).

Golden Bullets: The "bullet" cluster 1ES0657-558 is a spectacular example where detailed observations in the X-ray and O/IR bands, plus weak gravitational lens modeling, are combined to constrain fundamental physics such as the nature of gravity, and Dark Matter cross-sections [15, 21].

3 New Horizons

The preceding summary was meant to give a flavor of the high level of activity in the field and the excitement that we feel looking ahead to the future. In the coming decade and beyond, we anticipate that even greater progress can be made in key areas related to cluster astrophysics. These would be enabled by a number of initiatives in various areas (with reference to companion white papers where they are known to us):

Theory and Modeling Refinements: Much of the progress made in understanding cluster astrophysics has been based on the tremendous improvements that have occurred in computational resources and algorithm development. The next challenge will be to advance our theoretical understanding of the micro-physics associated with plasma non-equilibrium processes such as shocks, turbulence, and magnetic dynamos and to connect those to astrophysical processes such as accretion disks, jet and star formation. Mapping the relevant physics within cosmological simulations, for example to track the baryonic (stellar and non-stellar) components [22], will require improvements in dynamic range and simulation fidelity. Understanding the results and limitations of simulations, carefully simulating the next generation of observational data sets for comparison, and the accurate extraction of astrophysical and cosmological parameters from large simulation runs, will all be challenges that must be met. These goals can be achieved by investment in the theory programs, and support for the development of innovative new algorithms and implementation in the future code base.

Universe in a Box: Realization of models in the form of large and/or detailed simulations will build upon the theory and modeling advancements. Much of the future progress will rely upon use of "top-500" class computational facilities. It is critical that astrophysical and cosmological researchers have funding for the deployment of and access to the cutting edge computational and access grid infrastructure of the future. Results from simulations will need to be accessible by the theorists and observers, in forms that can be efficiently analyzed. This is a trend across science disciplines, and participation in cross-cutting programs with computing centers and funding divisions will likely be necessary to ensure that astrophysical computing needs are met.

Observational Frontiers: A vigorous and broad program of multi-wavelength surveys and new observational facilities will be needed to exploit the advances in theory and modeling. Radio facilities at meter and centimeter wavelengths will discover and image the synchrotron radiation from active and relic regions within clusters [23]. Substantial increases in sensitivity and resolution at the lowest frequencies are particularly needed to go deeper as well as to improve upon the first-generation radio sky surveys. Millimeter and submillimeter observations will probe the thermal pressure and velocity structure through the SZ effect [24], with high-resolution observations pinpointing active star formation. A combination of wide bandwidth large-format survey cameras and high-resolution high-sensitivity interferometric arrays provide the required capabilities. Optical and infrared surveys of galaxies will follow the stellar content, and through weak lensing map out the Dark Matter to increasing precision. The successors to the SDSS will be carried out using the next generation of ground and space-based O/IR survey telescopes outfitted with large state-of-the-art cameras, feeding follow-up programs using multi-object spectrographs on large apertures. X-ray observations will carry out calorimetry of the ICM, image shocked substructure [25] and diffuse cluster emission [26], and further our understanding of AGN feedback [27]. It is critical to have

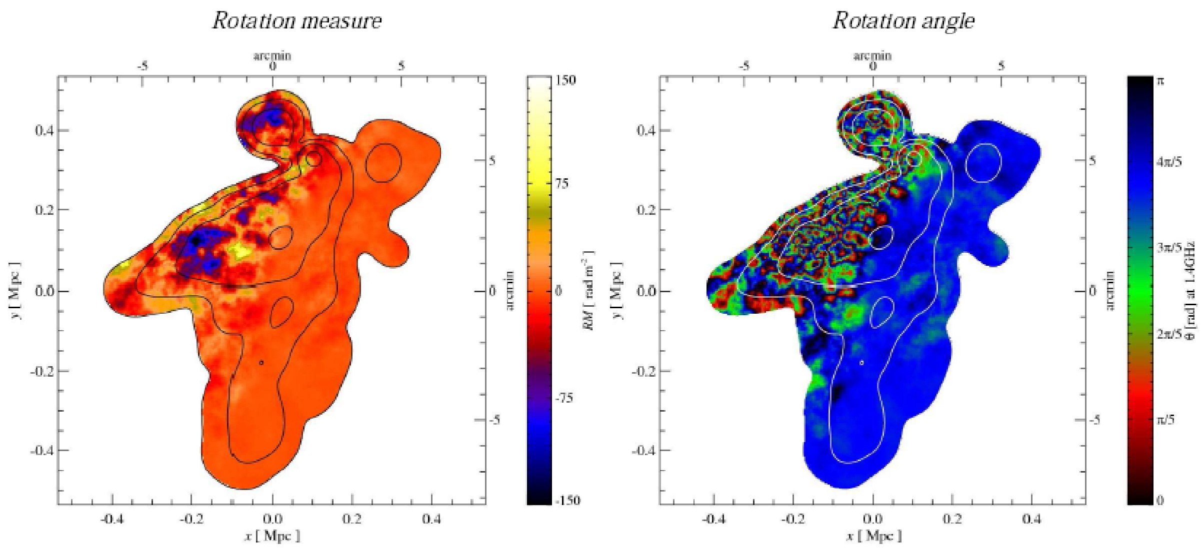

Figure 3: Simulated rotation measure (left) and 1.4GHz rotation angle (right) for an A2256-like cluster. Detailed study of magnetic field structure will be possible in the coming decade with new and improved low-frequency radio arrays. Taken from Figure 5 of [19].

future X-ray missions to follow Chandra and XMM-Newton, and to compile the next all-sky cluster survey. Finally, high energy X-rays and Gamma rays can be used to constrain Dark Matter through annihilation emission, and to probe the high energy tail of shock and jet accelerated particles. The combination of all of these in the acquisition of extremely large samples of clusters for cosmology will enable precision measurements of parameters such as the Dark Energy equation of state complementary to those provided by fine-scale CMB [28] and optical surveys.

4 Conclusions

It is clear that our understanding of cluster astrophysics has blossomed in the past decade due to the convergence of theoretical, computational, and observational advancements. In turn, the recognition that cluster surveys can be used for cosmology has kicked off a new generation of ambitious observational programs on a variety of facilities. The success of these programs will hinge on our ability to understand the nature and evolution of clusters. We have outlined key questions and focus areas in this subject for concentration in the coming decade. We support a strategy that leverages investment in theory programs, progress in computational infrastructure and improved access to computing and data products, and the adoption of a science road map that makes use of precursor research from key near-term projects and pathfinder telescopes, as well as engenders the design, construction and operation of the important next-generation facilities (both small and large). The science program for cluster astrophysics and cosmology truly spans the electromagnetic spectrum, crossing boundaries between modeling and observing techniques, and is thus an ideal focus for the coming decade.

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