# Plasma Physics in Clusters of Galaxies

## A White Paper Submitted to the Astro2010 Decadal Survey Committee

Benjamin D. G. Chandran, University of New Hampshire
Prateek Sharma, University of California, Berkeley
Ian J. Parrish, University of California, Berkeley

Endorsed by the Topical Group in Plasma Astrophysics of the American Physical Society

Endorsed by the Center for Magnetic Self-Organization in Laboratory & Astrophysical Plasmas (www.cmso.info./), an NSF Physics Frontier Center in partnership with DoE

Science Frontier Panels
Primary: Galaxies Across Cosmic Time (GCT)
Secondary: Cosmology and Fundamental Physics (CFP)

# 1 Introduction

As the largest gravitationally bound objects in the Universe, galaxy clusters occupy a unique position within astrophysics. Not only can their properties be used to constrain cosmological parameters, but they also host an extraordinary range of dynamical processes, from AGN feedback, shock acceleration, and star formation near a cluster's center to the cluster-scale accretion of dark matter and plasma near a cluster's edge. Throughout the intracluster medium (ICM), magnetic fields, turbulence, infalling material, and ram-pressure stripping of galaxies lead to a fascinating, complex, and dynamic environment.

Although roughly 5/6 of a cluster's mass is comprised of dark matter, the remaining 1/6 is primarily in the form of hot ($\sim 2-10$ keV) intracluster plasma. The physics of this plasma is thus essential for understanding the observable properties of clusters. Because the ICM is magnetized (with roughly $\mu G$ magnetic fields), the physical processes operating in the ICM are not captured by a simple hydrodynamic description. For example, thermal conduction is anisotropic in the ICM, with heat flowing rapidly along the (tangled) magnetic field lines, but only slowly across these field lines. In part because of this anisotropy, the basic convective stability of the ICM differs greatly from that of a stellar interior. As we will describe further below, the ICM is always convectively unstable (!), regardless of the sign of the entropy and temperature gradients.

In this White Paper, we wish to emphasize that plasma physics has an essential role to play in the study of galaxy clusters in the coming decade. For example, one of the most important problems in the study of clusters at the present time is the "cooling-flow problem," which amounts to explaining why there is relatively little cooling of intracluster plasma to low temperatures in cluster cores, despite the fact that the radiative cooling time is much shorter than a cluster's age. As we will describe further below, future investigations in astrophysical plasma physics will be crucial for addressing this problem, and in particular for understanding how the mechanical luminosity of a central AGN can be converted into heating of the diffuse ICM. Advances in astrophysical plasma physics will also be important for understanding the origin and nature of intracluster magnetic fields, and for the transport of heat, momentum, and cosmic rays in the ICM. Plasma-physics investigations in these areas, coupled closely to astrophysical modeling, will also be important for interpreting future observations of relativistic particles and magnetic fields from *Fermi* and the Extended VLA.

In section 2 we provide some background on the cooling-flow problem and describe current thinking on the processes that govern the thermal balance in the ICM. In section 3 we describe specific advances in plasma physics that are needed in order to understand the interaction between AGN and the ICM, as well as the more general problems of the convective stability and temperature profile of the ICM. In section 4 we briefly describe two other plasma-physics problems that are important for clusters: the role of small-scale plasma instabilities driven by pressure anisotropy, and the origin of galaxy-cluster magnetic fields.

## 2 The Cooling-Flow Problem

X-ray observations provide a detailed picture of the temperature and density profiles of intracluster plasmas, and show that in most clusters the radiative cooling time near the cluster's center ($\sim 10^8 - 10^9$ yr) is much shorter than a cluster's age ($\sim 10^{10}$ yr). A historically influential model for the ICM, the "cooling-flow model," hypothesized that there is no heat source to offset the radiative cooling in clusters. In the model, plasma cools and flows inward subsonically, eventually cooling to very low temperatures near the cluster's center. Because of the enormous amount of intracluster plasma and the relatively short cooling times, the rate at which plasma is predicted to cool to low temperatures in the model is very large, exceeding $1000 M_\odot$ yr$^{-1}$ in some clusters [1]. However, such large cooling rates have now been definitively ruled out by high-spectral-resolution X-ray observations from XMM-Newton, which place strict upper limits on the strength of O VIII and Fe XVII emission lines, which in turn measure the rate at which plasma cools to temperatures $\lesssim 10^7$ K. These upper limits constrain the actual cooling-rate in clusters to be less than about one-tenth of the cooling-flow model prediction [2, 3, 4].

Although the XMM-Newton measurements solved one problem (whether the cooling-flow model works), they highlighted another: what stops the intracluster plasma from cooling to low temperatures? This is the "cooling-flow problem." A number of heating mechanisms have been proposed over the years, including thermal conduction, supernovae, galaxy motions, and AGN feedback. However, the first three of these mechanisms are incapable of offsetting cooling in cluster cores [5, 6, 7]. (Thermal conduction could potentially balance cooling in some clusters, but not in many others [5].) The currently favored paradigm invokes heating from a central AGN, with additional heating provided to some extent by thermal conduction.

Perhaps the strongest arguments in favor of AGN feedback are that (1) almost every strongly cooling cluster core possesses an active central radio source [8], (2) the X-ray luminosity of the intracluster plasma within a cluster's core is correlated with both the mechanical luminosity [9] and radio luminosity [10] of the central AGN, and (3) AGN feedback is self-regulating, so that no fine-tuning of parameters is required in order for heating to balance cooling [11]. The idea behind this last point is that the AGN feedback power is proportional to the rate at which cooling intracluster plasma feeds the central supermassive black hole (an idea supported by the observed correlation between the mechanical luminosity of AGNs in elliptical galaxies and the Bondi accretion rate calculated using observed temperatures and densities [12]). Thus, if the AGN power becomes too large, the AGN shuts off its fuel supply by over-heating the ICM, and the AGN feedback power drops back to its equilibrium level. Conversely, if the accretion rate and AGN mechanical luminosity drop too far, then the intracluster plasma cools rapidly, increasing the accretion rate of the central black hole, and the AGN feedback heating then grows, reducing the rate at which intracluster plasma cools.

Although the arguments in favor of AGN heating are compelling, it is not yet clear how or if an AGN's power could be transferred to the diffuse intracluster plasma. For example, the most straightforward energetic link, Compton heating via the AGN's radiative luminosity, is too weak to solve the cooling-flow problem by about two orders of magnitude [13]. If AGN heating is the answer, it must involve the mechanical luminosity of the AGN. However, whether an AGN's mechanical luminosity can be efficiently converted into heating of the diffuse intracluster plasma, and how this conversion would take place, remain unknown. Determining the processes that govern the exchange of energy between a central AGN and intracluster plasma is thus at the forefront of the community's efforts to solve the cooling-flow problem.

Solving the cooling-flow problem is one of the highest priorities in the study of clusters for a number of reasons. The regulation of the central temperature in clusters is a key feature of a cluster's structure, affecting the star-formation rate in the central Brightest Cluster Galaxy (BCG) as well as statistical measures such as the cluster mass-luminosity and luminosity-temperature relations. These scaling relations play an important role in enabling clusters to be used to probe and constrain cosmological parameters. The solution to the cooling-flow problem also likely solves the "over-cooling problem," which is the discrepancy between the observed fraction of cluster baryons that have formed stars ($\sim 15\%$) and the larger fraction ($\sim 40\%$) that cools to form stars in numerical simulations in which supernovae provide the only form of non-gravitational heating [14]. In addition, black-hole feedback plays an important role in galaxy formation, and advances in our understanding of AGN feedback in clusters will provide insights into the mechanisms that truncate the galaxy luminosity function at large luminosities.

# 3 Plasma Physics and AGN Feedback

Some hints at how an AGN's mechanical luminosity could be converted into diffuse plasma heating are provided by X-ray observations, which reveal the presence of "cavities" or "bubbles" in approximately 25% of the clusters in the *Chandra* archive [9]. The thermal plasma in these bubbles is depleted relative to the surrounding environment. Radio observations indicate that many of these cavities are associated with enhanced levels of synchrotron-emitting cosmic-ray electrons. The cavities are presumably filled with cosmic-ray protons as well, with both electrons and protons accelerated in shocks that arise when jets from the central AGN collide with the surrounding ICM. The observed cavities are typically $\sim 10$ kpc in diameter, and located within the central $\sim 20$ kpc of a cluster [9] [the whole cluster having a (virial) radius of $\sim 1-2$ Mpc]. The power requirements for "inflating" these cavities are comparable to the radiative cooling rates of cluster cores [9], suggesting that these bubbles, and perhaps the cosmic rays that fill them, are involved in the feedback process.

Because cosmic rays provide pressure without appreciably increasing the mass density, cosmic-ray-enriched plasma is buoyant, suggesting that AGN feedback could contribute to convection in the intracluster medium. Convection in the ICM was for a long time discounted, since the density falls off with radius quite rapidly, leading to a highly stabilizing entropy gradient. However, analytical and numerical investigations over the last decade have shown that in a low-density magnetized plasma, the anisotropic nature of heat conduction (rapid along field lines, slow across field lines) profoundly alters the nature of convective stability in the ICM, and the Schwarzchild criterion ($ds/dr > 0$) does not apply. In fact, a plasma with thermal conduction only along magnetic field lines is buoyantly unstable, irrespective of the sign of both $ds/dr$ and $dT/dr$. When the temperature decreases outwards, plasma with non-radial magnetic field lines becomes unstable to the magnetothermal instability, which saturates by making the field lines radial [15, 16, 17, 18]. When the temperature increases outwards, plasma with a non-vanishing radial magnetic-field component (and hence a background heat flux) becomes unstable to the heat-flux-buoyancy instability, which saturates by making the field lines aligned perpendicular to gravity [19, 20]. (In stellar interiors, on the other hand, heat is conducted primarily by photons, so that the conductivity is isotropic, leading to the familiar Schwarzchild criterion.)

Cosmic rays also contribute to buoyancy instabilities in the ICM [21]. Because the thermal plasma is itself convectively unstable, the turbulence triggered by cosmic-ray buoyancy is much more vigorous than it would be if the intracluster plasma were treated as a hot gas with a highly stabilizing entropy gradient[1] [22]. Convective turbulence can then heat the intracluster plasma through the dissipation of turbulent motions, providing a vehicle for converting an AGN's mechanical luminosity into a heat source for the diffuse plasma in a large fraction of the cluster-core volume. (In addition to this convective heating, cosmic rays can also heat the intracluster plasma by exciting magnetohydrodynamic waves that are subsequently damped [23, 24]).

These recent advances in the theory of convection in the ICM highlight a theme that is appearing increasingly in different areas of astrophysics, from clusters and accretion disks to shock acceleration and the solar wind: the microphysics of plasma behavior is critical for explaining the observable, macroscopic evolution of the system. In the case of clusters and convection, advances in our understanding of buoyancy instabilities are forcing a major revision of our understanding of the dynamics and structure of the ICM. Recent work on convective clusters with AGN feedback that takes into account some of the physics just described suggests that convection could be an integral part of the solution to the cooling-flow problem [25]. However, many more plasma-physics-related problems need to be addressed in the coming decade before the role of buoyancy instabilities and convection in the ICM becomes clear, including the following:

- How do these buoyancy instabilities saturate? Do they drive turbulence and strong convection to a sufficient degree to offset cooling in cluster cores?
- How are the instabilities affected by anisotropic plasma viscosity, and how do they

[1] See `http://astro.berkeley.edu/~psharma/clustermovie.html`

depend on the rate of cosmic-ray diffusion?

- How do buoyancy instabilities and convection fit into the larger picture of AGN feedback, including radiative cooling by intracluster plasma and accretion of intracluster plasma in the vicinity of the central AGN?
- What is the relation between these buoyancy instabilities and the large-scale temperature profile of the ICM? How do buoyancy instabilities affect the baryons during the formation of a cluster? Do buoyancy instabilities and convection help us to understand the mass-luminosity and luminosity-temperature relationships for clusters?

Multidimensional numerical modeling, incorporating thermal conduction along field lines [16, 17, 18, 20] and cosmic rays [22, 26, 27], has already begun to address these questions, and will be an essential component of future investigations into the cooling-flow problem. *Observationally, one of the most useful instruments for exploring the physics of turbulence and convection in clusters would be a high-spectral-resolution imaging X-ray spectrometer (calorimeter), which could directly measure turbulent velocities in the ICM.*

Another area of active research involving plasma physics that will be important for addressing the cooling-flow problem during the coming decade is the interaction between jets and the ICM. In recent years, increasingly high-resolution numerical simulations have helped to elucidate different aspects of this interaction, including the extent to which jets can "drill through" the ICM and the escape of cosmic rays from cosmic-ray bubbles [26, 28, 29]. Although anisotropic diffusion of cosmic rays has been included in recent simulations [26], the inclusion of anisotropic viscosity will be important for determining the rate at which cosmic-ray bubbles break up,[2] while the inclusion of anisotropic conductivity will be essential for determining the extent of turbulent mixing in the ICM.

# 4 Other Important Plasma-Physics Problems in Clusters of Galaxies

In addition to the cooling-flow problem, there are a number of other problems in the study of clusters in which plasma physics plays a prominent role. For example, the Extended VLA promises to provide much greater detail into the nature of intracluster magnetic fields, by allowing for Faraday rotation studies of a much larger sample of background radio sources whose lines of sight pass through the ICM. To interpret and understand these observations, it will be necessary to first understand the origin of intracluster magnetic fields. Two of the competing paradigms are that (1) cluster fields originate from plasma and fields expelled by extragalactic radio sources, and (2) that the fields originate from a turbulent dynamo

[2] In intracluster plasma, the viscosity perpendicular to field lines is very small, so there is very little viscous damping of "interchange-like" motions in which nearly parallel field lines slip by one another.

operating in the ICM. There are, however, major unsolved puzzles for both paradigms. For example, how could fields from jets avoid the flux-freezing constraint, which implies that the magnetic fields from a jet would be reduced in strength by many orders of magnitude as the field expands (or diffuses into intracluster plasma) to fill the ICM. For fields originating in a turbulent dynamo, how could such fields obtain a coherence length of $\sim 5-20$ kpc, when existing dynamo theories that successfully predict such large-scale coherence rely upon rotation, which is largely absent in clusters?

Another plasma-physics problem that is important for clusters is the role of pressure-anisotropy-driven plasma instabilities, such as the firehose instability and mirror instability. These small-scale instabilities arise when larger-scale motions perturb the magnetic field strength on a time scale shorter than the Coulomb collision time but longer than a particle's cyclotron period. Turbulent motions in the ICM lead to such field-strength perturbations, and thereby cause the rapid amplification of very-small-scale magnetic fields, which modify the viscosity and conductivity in ways that are not yet fully understood [30].

# 5 Conclusion

The fundamental message that we wish to convey in this White Paper is that an accurate treatment of the plasma physics of clusters is essential for solving important problems in this area, and in particular the cooling-flow problem. Hydrodynamic and MHD models with isotropic conduction and viscosity have enabled us to understand some of the physics of the ICM, but it is becoming increasingly clear that critical aspects of the ICM depend upon the anisotropy of the plasma conductivity and viscosity. Modeling of the ICM that takes this plasma physics into account is leading to a transformation in the way that we understand the fundamental structure (and in particular the convective stability) of the ICM. Further work on convection in the ICM and the role of anisotropic transport promises to deepen our understanding of the interaction between central AGN and the surrounding ICM, and will potentially lead to important progress towards a solution of the cooling-flow problem. This work (with its implications for turbulent diffusion of cosmic rays in the ICM) and investigations into the origin of cluster magnetic fields will also help us to interpret future observations of relativistic particles and magnetic fields from *Fermi* and the Extended VLA.

# References

[1] Fabian, A. C. 1994, Ann. Rev. Astr. Astrophys., 32, 277

[2] Böhringer, H. et al 2001, A&A, 365, L181

[3] David, L. P., Nulsen, P. E. J., McNamara, B. R., Forman, W., Jones, C., Ponman, T., Robertson, B., Wise, M. 2001, ApJ, 557, 546

[4] Peterson, J. R., et al 2001, A&A, 365, L104

[5] Zakamska, N., & Narayan, R. 2003, ApJ, 582, 162
[6] Domainko, W., Gitti, M., Schindler, S., & Kapferer, W. 2004, A&A, 425, L21
[7] Kim, W., El-Zant, A., & Kamionkowski, M. 2005, ApJ, 632, 157
[8] Ball, R., Burns, J. O., & Loken, C. 1993, AJ, 105, 53
[9] Birzan, L., Rafferty, D., McNamara, B., Wise, M., & Nulsen, P. 2004, ApJ, 607, 800
[10] Eilek, J. 2004, in *The Riddle of Cooling Flows and Clusters of Galaxies*, ed. Reiprich, T., Kempner, J., & Soker, N., E13, **http://www.astro.virginia.edu/coolflow/proc.php**
[11] Rosner, R., & Tucker, W. 1989, ApJ, 338 761
[12] Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, MNRAS, 372, 21
[13] Ciotti, L., & Ostriker, J., & Pellegrini, S. 2004, in *Plasmas in the Laboratory and in the Universe: New Insights and New Challenges*, AIP Conf. Proc., 703, 367
[14] Nagai, D., & Kravtsov, A. 2004, in IAU Colloq. 195, Outskirts of Galaxy Clusters: Intense Life in the Suburbs, ed. A. Diaferio (Cambridge: Cambridge Univ. Press), 296
[15] Balbus, S. 2001, ApJ, 562, 909
[16] Parrish, I. J., & Stone, J. M. 2005, ApJ, 633, 334
[17] Parrish, I. J., & Stone, J. M. 2007, ApJ, 664, 135
[18] Sharma, P., Quataert, E., & Stone, J. M. 2008, MNRAS, 389, 1815
[19] Quataert, E. 2008, ApJ, 673, 758
[20] Parrish, I. J., & Quataert, E. 2008, ApJ, 677, L9
[21] Chandran, B., & Dennis, T. 2006, ApJ, 642, 140
[22] Sharma, P., Chandran, B. D. G., Quataert, E., & Parrish, I. J. 2009, arXiv:0901.4786
[23] Loewenstein, M., Zweibel, E., & Begelman, M. 1991, ApJ, 377, 392
[24] Guo, F., & Oh, S. P. 2008, MNRAS, 384, 251
[25] Chandran, B., & Rasera, Y. 2007, ApJ, 671, 1413
[26] Ruszkowski, M., Ensslin, T. A., Brüggen, M., Begelman, M. C., & Churazov, E. 2008, MNRAS, 383, 1359
[27] Mathews, W. G., & Brighenti, F. 2008, ApJ, 685, 128
[28] Heinz, S., Brüggen, M., Young, A., Levesque, E. 2006, MNRAS, 373, L65
[29] Vernaleo, J. C., & Reynolds, C. S. 2006, ApJ, 645, 83
[30] Schekochihin, A. A., Cowley, S. C., Kulsrud, R. M., Rosin, M. S., & Heinemann, T. 2008, Phys. Rev. Lett., 100, 081301