Astro2020 Science White Paper

Physics of cosmic plasmas from high angular resolution X-ray imaging of galaxy clusters

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:
Galaxy clusters are massive dark matter-dominated systems filled with X-ray emitting, optically thin plasma. Their large size and relative simplicity (at least as astrophysical objects go) make them a unique laboratory to measure some of the interesting plasma properties that are inaccessible by other means but fundamentally important for understanding and modeling many astrophysical phenomena — from solar flares to black hole accretion to galaxy formation and the emergence of the cosmological Large Scale Structure. While every cluster astrophysicist is eagerly anticipating the direct gas velocity measurements from the forthcoming microcalorimeters onboard *XRISM*, *Athena* and future missions such as *Lynx*, a number of those plasma properties can best be probed by high-resolution X-ray *imaging* of galaxy clusters. *Chandra* has obtained some trailblazing results, but only grazed the surface of such studies. In this white paper, we discuss why we need arcsecond-resolution, high collecting area, low relative background X-ray imagers (with modest spectral resolution), such as the proposed *AXIS* and the imaging detector of *Lynx*.

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MODERN astrophysics relies on computer simulations to help us understand complex phenomena in the Universe, from solar flares to supernova explosions, black hole accretion, galaxy formation and the emergence of Large Scale Structure. As supercomputers advance, the benefits of numeric simulations will grow. However, for systems that include plasma, there is a fundamental limitation — we can't simultaneously model all the relevant linear scales from first principles. For example, turbulence in the cosmological volume is driven by structure formation on the galaxy cluster scale (10^{24} cm), but can cascade down to scales as small as the ion gyroradius (10^{8-9} cm), a dynamic range that is impossible to implement in codes. To model such systems, we have to rely on observed plasma properties and encode them at the "subgrid" level. However, many properties that affect large-scale phenomena — viscosity, heat conductivity, energy exchange between the particle populations and the magnetic field — are still unmeasured and their theoretical estimates uncertain by orders of magnitude because of the complexity of the plasma physics. Of course, apart from being "under the hood" of many astrophysical systems, plasma physics is interesting on its own.

Mircoscale phenomena in $\beta \sim 1$ plasmas (where β is the ratio of thermal to magnetic pressure) can be studied in situ in our space neighborhood. Larger scales, including the transition from "kinetic" to "fluid" regime, can be probed in another natural laboratory that is galaxy clusters. Clusters are Megaparsec-size clouds of X-ray emitting, optically thin plasma (ICM), permeated by tangled magnetic fields and ultrarelativistic particles, with typical $\beta >$ 100. This regime is directly relevant for many astrophysical systems, among them SNR, accretion disks and the intergalactic medium.

Several phenomena observed in clusters are sensitive to plasma physics. Turbulence is one, and it will be characterized by the future microcalorimeters (*XRISM* and *Athena*) using Doppler shifts of the X-ray emission lines. Several important measurements can be done using high-resolution X-ray *imaging*. Shock fronts, discovered by *Chandra* thanks to its sharp mirror, let us study heat conductivity, the electron-ion temperature equilibration and the physics of cosmic ray acceleration[1]. Another interesting plasma probe is provided by the ubiquitous, sharp contact discontinuities, or "cold fronts"[1]. While *Chandra* has obtained tantalizing results, it has only scratched the surface of what can be learned from detailed imaging of these and some other cluster phenomena.

PLASMA EQUIPARTITION TIMES

The common assumption that all particles in a plasma have the same local temperature may not be true if the electron-ion equilibration timescale is longer than heating timescales[3,4]. This timescale is fundamental for such processes as accretion onto black holes and X-ray emission from the intergalactic medium. It can be directly measured using cluster shocks.

At a low-Mach shock, ions are dissipatively heated to a temperature T_i, while electrons are adiabatically compressed to a lower T_e. The two species then equilibrate to the mean post-shock temperature[5] (Fig. 1). From the X-ray brightness and spectra, we can measure the plasma density and T_e across the shock (this requires only a modest spectral resolution). For the typical low sonic Mach numbers in clusters ($M = 2-3$), the mean post-shock temperature can be accurately predicted from the shock density jump. If the equilibration is via Coulomb collisions, the region over which the electron temperature T_e increases is tens of kpc wide — resolvable with a *Chandra*-like telescope at distances of $z < 2$. This direct test is unique to cluster shocks because of the fortuitous combination of the linear scales and relatively low Mach numbers; it cannot be done for the solar wind or SNR shocks.

A *Chandra* measurement for the Bullet cluster shock (Fig. 1) suggests that $T_e - T_i$ equi-

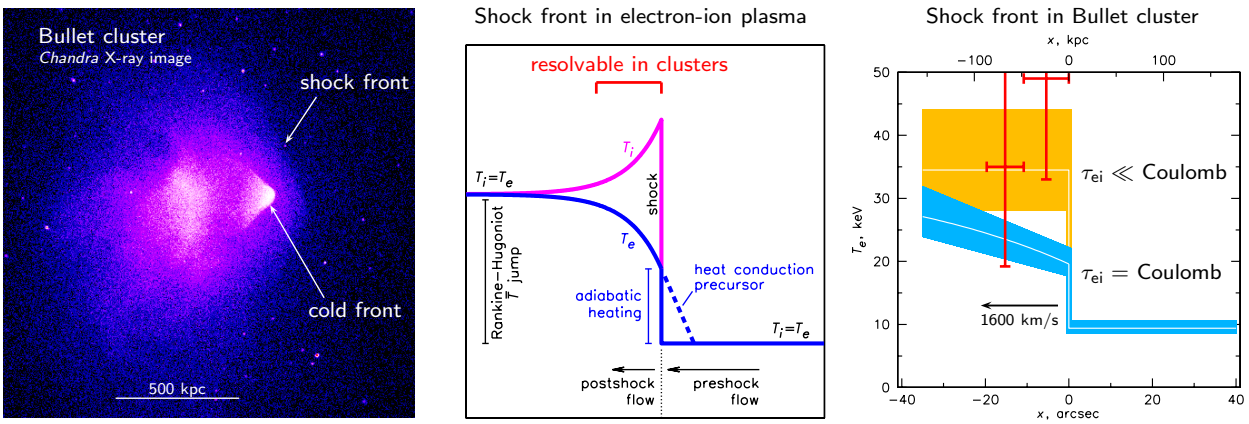

Fig. 1 — (*a*) X-ray image of the Bullet cluster, the textbook example of a bow shock. The shock is driven by a moving subcluster, whose front boundary is a "cold front." (*b*) Expected electron and ion temperature profiles across a shock front. Temperatures are unequal immediately after the shock and then equalize. If electron heat conduction is not suppressed, a temperature precursor is also expected. (*c*) *Chandra* deprojected electron temperature profile immediately behind the Bullet shock (crosses; errors are 1σ) with models for Coulomb collisional and instant equipartition[2]. This measurement favors fast electron-proton equilibration, but uncertainties are large.

libration is quicker than Coulomb[2], although with a systematic uncertainty that arises from the assumption of symmetry and requires averaging over a sample of shocks. With *Chandra*, this measurement is limited to only three shocks, and the results are contradictory[2,6,7]. A more sensitive imager is needed to find many more shocks (most of them in the cluster outskirts), select a sample of suitable ones, and robustly determine this basic plasma property.

HEAT CONDUCTIVITY

Heat conduction erases temperature gradients and competes with radiative cooling, and is of utmost importance for galaxy and cluster formation. The effective heat conductivity in a plasma with tangled magnetic fields is unknown, with a large uncertainty for the component parallel to the field, which recent theoretical works predict to be reduced[11–15]. The existence of cold fronts in clusters confirms that conduction across the field lines is very low[16–18], but constraints for the average or parallel conductivity are poor[18,19]. Shock fronts are locations where the parallel component can be constrained, because the field lines should connect the post-shock and pre-shock regions (unlike for the magnetically-insulated cold fronts), though the field structure in the narrow shock layer can be chaotic. Electron-dominated conduction may result in an observable T_e precursor (Fig. 1).

The magnetic field can be stretched and untangled in a predictable way in the cluster sloshing cool cores. The characteristic spiral temperature structure that forms there[20] can also be used to constrain parallel conductivity. A telescope with a bigger mirror than *Chandra*'s could look for temperature precursors in shocks and obtain detailed maps of temperature gradients along the field filaments in many cluster cores to measure the conductivity.

VISCOSITY

Plasma viscosity is a fundamental quantity that governs damping of turbulence and sound waves, suppression of hydrodynamic instabilities and mixing of different gas phases, and thus relevant to such important processes as heating the gas, spreading metals ejected from galaxies, and amplification of magnetic fields. At present it is largely unknown. Isotropic

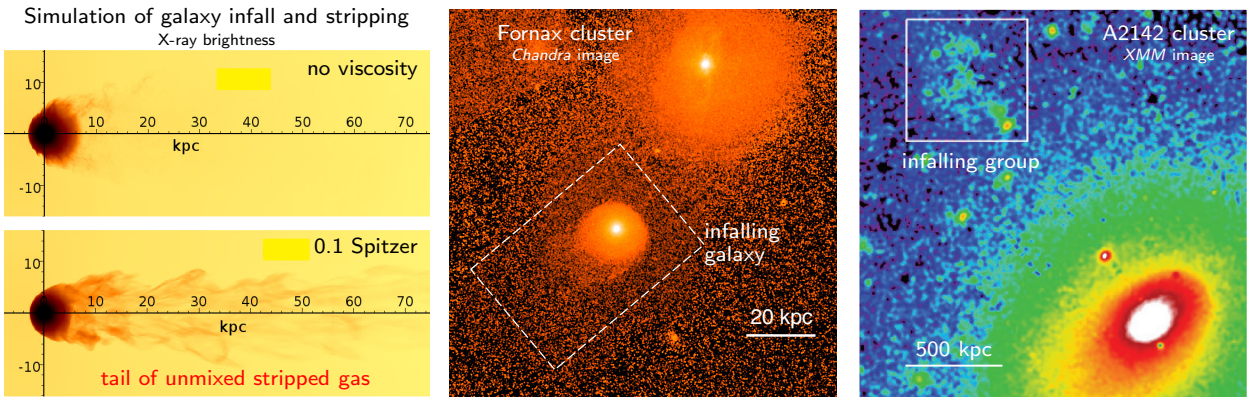

Fig. 2 — Plasma viscosity determines how the gas is stripped from the infalling groups and galaxies. *Left*: If viscosity is not strongly suppressed, galaxies falling into clusters should exhibit prominent tails of stripped gas[8]. *Middle, right*: An infalling galaxy (NGC1404), which appears not to have such a tail[9], and a much larger infalling group in the outskirts of a cluster[10], which does.

viscosity can be determined from the dissipation scale of the power spectrum of turbulence. *XRISM* and *Athena* will pursue that via the velocity measurements in the ICM, though it is unclear if the dissipation scale will be reachable[21]. The turbulence spectrum can also be constrained by observing the gas density fluctuations[22,23]. However, the plasma viscosity should be anisotropic and may affect turbulence and other phenomena differently. It is thus useful to approach it from several angles. Two subtle phenomena in galaxy cluster images can help us probe the viscosity through its effect on gasdynamic instabilities.

Galaxy stripping tails. Figure 2*a* shows a striking difference in the simulated X-ray appearance of the tail of the cool stripped gas behind a galaxy as it flies through the ICM[8]. In an inviscid plasma, the gas promptly mixes with the ambient ICM, but a modest viscosity suppresses the mixing and makes the long tail visible. Deep *Chandra* images of such infalling galaxies NGC1404 (Fig. 2*b*) and M89 favor efficient mixing and a reduced viscosity[9,24]. Other infalling groups in the cluster periphery do exhibit unmixed tails (e.g., Fig. 2*c*). This points to a possibility of a systematic study to constrain effective viscosity — and directly observe its effect on gas mixing — in various ICM regimes. However, a more sensitive instrument with lower background is required to study these subtle, low-contrast extended features, most of which will be found in the low-brightness cluster outskirts.

Instabilities in cold fronts. Cold fronts — contact discontinuities in the ICM that separate regions of different density and temperature in pressure equilibrium[1] — are ubiquitous in merging subclusters, where they are seen as sharp X-ray brightness edges (e.g., the "bullet" boundary in the Bullet cluster, Fig. 1*a*). They are also found in most cool cores, where they emerge as the dense gas of the core "sloshes" in the cluster gravitational well[26]. Sloshing produces velocity shear across the cold front, which should generate Kelvin-Helmholtz instabilities (Fig. 3*a*). If the ICM is viscous, K-H instabilities are suppressed[27–29] (Fig. 3*b*). *Chandra* has discovered K-H instabilities in a few cold fronts and placed an upper limit on the effective isotropic viscosity of ~ 0.1 Spitzer[30–32] (or, equivalently in this context, a full Braginskii anisotropic viscosity[29]). To constrain the viscosity from below requires finding instabilities for a range of density contrasts. These subtle wiggles can be seen only with high resolu-

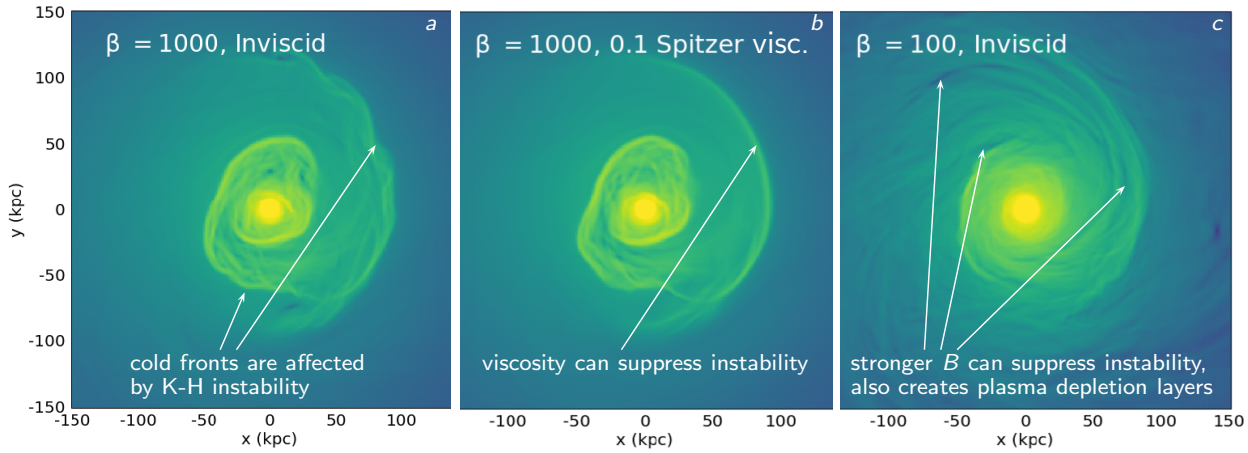

Fig. 3 — MHD simulation of a sloshing cluster core with viscosity (isotropic) and magnetic field[25]. X-ray brightness gradients are shown. Initial β values are given; sloshing amplifies the magnetic field and produces lower β, which result in plasma depletion regions. The appearance of cold fronts can be used to constrain the effective plasma viscosity and magnetic field strength.

tion and lots of photons, and a systematic study requires a larger-area telescope.

PLASMA DEPLETION LAYERS

The velocity shear at cold fronts (and elsewhere in the cluster) should stretch and amplify the magnetic fields, forming magnetic layers parallel to the front. Such layers can suppress the instabilities even without the viscosity[33], although a certain initial field strength is required (compare Figs. 3*a,c*). A distinguishing feature between these two suppression mechanisms is seen in Fig. 3*c*. Wherever the field is amplified, thermal plasma is squeezed out, forming plasma depletion layers (PDL, like the ones in the solar wind around planets[34]) that can become visible in the X-ray image[1].

In Fig. 4, we show how PDL can form in a sloshing core. *Chandra* has reported hints of this new phenomenon — low-contrast "channels" in A520 and A2142[18,32] and "feathery" structures in Virgo and Perseus[36,37], Fig. 4c). Apart from disentangling the effects of viscosity and magnetic fields on cold front stability, observing PDL in clusters would have a more general significance — it allows us literally to see the structure of the intracluster magnetic field. Combined with the radio images, this can map the distribution of cosmic ray electrons in the ICM. Observing these subtle image features requires many more photons than *Chandra* can collect for most clusters. A future imager with a much bigger mirror can give us this novel tool for cluster plasma studies.

COSMIC RAY ACCELERATION

Across the universe, shocks accelerate particles to very high energies via the first-order Fermi mechanism[38]. Microscopic details of this fundamental process remain poorly known for astrophysical plasmas, and particle-in-cell simulations are still far from covering realistic plasma parameters.

Many galaxy clusters exhibit striking "radio relics" in their outskirts[39]. These Mpc-long, arc-like structures are synchrotron signatures of ultrarelativistic ($\gamma \sim 10^4$) electrons. Some relics, as well as sharp edges of giant radio halos, coincide with ICM shocks[7,40,41], suggesting that shocks have something to do with those electrons. However, the shock Mach numbers are low ($M = 1.5 - 3$) and it is unclear how they reach the acceleration efficiency needed to produce the relics[42,43]. Other puzzles include similar-Mach shocks that produce very different radio features[41] and a relic for which

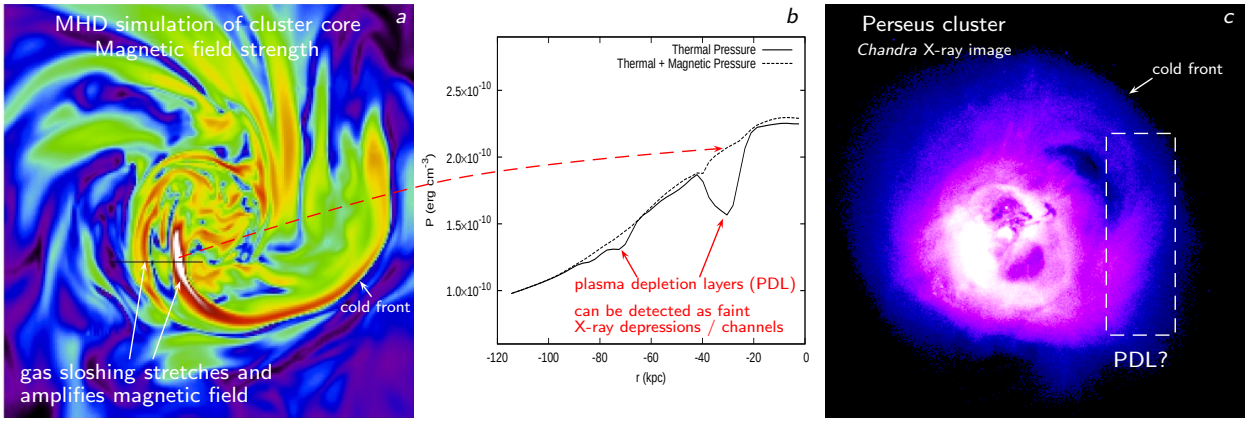

Fig. 4 — Plasma depletion layers in a cluster core. (*a*) MHD simulation of a sloshing core[35]; color shows the field strength. As the gas swirls in the core, it forms filaments of stretched and amplified field. (*b*) Pressure profiles across two $\beta \sim 10$ filaments, extracted along the line in panel *a*. While total pressure is monotonic, thermal pressure shows dips (both the density and the temperature dip). (*c*) Possible observation of such "feathery" structure in the Perseus core[36]. Subtle X-ray "channels," possibly of similar origin, have also been seen by *Chandra* in A520[18] and A2142[32].

the shock is ruled out[44]. Particle acceleration in the ICM appears more complex than a classical Fermi picture. Proposed solutions involve re-acceleration of aged relativistic particles[43] as well as modifications to the Fermi mechanism in a magnetized plasma. To gain insight into these universal processes, we need a systematic comparison of shocks in the X-ray and radio. However, most radio relics are found far in the cluster outskirts, where the X-ray emission is too dim for *Chandra*. A low-background, high-area, high-resolution X-ray imager is needed to discover and study shocks there.

FINDING MOST POWERFUL AGN OUTBURSTS

AGN that reside in many cluster cores eject copious amounts of energy into the ICM, preventing runaway radiative cooling of the gas at the cluster centers[45]. They inflate X-ray cavities in the ICM; radio observations show that these cavities are filled with relativistic plasma. A recent discovery of a giant ghost bubble outside the core in Ophiuchus[46] suggest that the AGN effects may extend far beyond the cluster cool cores, and that AGN can produce far more powerful outbursts than we infer from the energetics of the cavities in the cluster cores[47]. If this phenomenon is widespread, as hinted at by recent low-freqency radio surveys by *LOFAR* and *MWA*, clusters can be affected more strongly by the AGN feedback than previously thought. Forensic evidence for that can be provided by large, low-contrast ghost cavities outside cluster cores[48]. Their detection requires a low-background, high-area X-ray imager.

WHAT KIND OF INSTRUMENT WE NEED

All the above studies require a much greater collecting area and much lower background than the current X-ray instruments can provide. Critically, they also require high angular resolution — at least *Chandra*-like — both to resolve the sharp spatial features and to remove the faint point sources of the Cosmic X-ray Background that dominate the flux in the cluster outskirts, where most of those features will be found. *AXIS*, a proposed Probe, and the imaging detector of *Lynx*, a proposed Flagship, will have the requisite resolution and photon-collecting capabilities. They will also enable unsurpassed low-background imaging for $E >$ 1 keV (where the soft diffuse Galactic background becomes insignificant), as shown in the accompanying white paper[49].

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