



The stormy life of GALAXY CLUSTERS

OPTICAL IMAGE OF COMA CLUSTER GALAXIES

(courtesy of Bob Franke, Focal Pointe Observatory).
Background from EAGLE computer simulation illustrating
infalling dark matter and baryons (courtesy of Richard
Bower; J. Shaye et al., *Mon. Not. R. Soc.* **446**, 521, 2015).

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Tempestuous interactions between plasmas, galaxies, and dark matter have shaped the history and current structure of the universe.

It's 1902 and astronomer Max Wolf is confused. Scrutinizing photographic plates of the star-poor region near the north pole of the Milky Way, in the constellation Coma Berenices, he spots an unusual concentration of fuzzy patches. In his article, "Die Nebelflecken am Pol der Milchstrasse" ("The fuzzy objects at the pole of the Milky Way"), Wolf provides meticulous descriptions of those objects, their sizes, and their morphologies—elliptical, spiral, and core brightened. He concludes with the understatement, "It would be premature to speculate on this strange result. Nonetheless, I must not miss pointing it out for general attention."¹

Thirty years later Wolf's fuzzy nebulae were shown to be island universes, what we now call galaxies, and first hypothesized by German philosopher Immanuel Kant. Today, Wolf's collection of galaxies is known as the Coma cluster—its central region of massive galaxies is shown in the opening image. They are each comparable in size to our own Milky Way, with hundreds of billions of stars.

But another mystery emerged in the early 20th century. Using the Doppler shifts of galaxies in the clusters, astronomers calculated that about 400 times the mass of the stars themselves would be required to keep clusters like Coma gravitationally bound. In 1933 the brilliant and eccentric Swiss astronomer Fritz Zwicky attributed that extra gravitational force to some unknown "dunkle Materie,"² or dark matter, whose nature remains a mystery to this day.

A brief glimmer of hope that dark matter might have been found appeared in the 1970s when as-

tronomers discovered that clusters of galaxies were filled with an x-ray-emitting plasma—the intracluster medium (ICM)—at a temperature of 10^7 – 10^8 K degrees. But estimates of its mass quickly established that it too fell far short of being able to bind the cluster. The ICM contributes only about 13% of the 10^{45} kg that make up the most massive clusters. Dark matter, whatever its nature, continues to dominate the overall cluster collapse and subsequent dynamical evolution.

Both computer simulations and observational studies of the three-dimensional distribution of mostly dark matter show that it is concentrated into filamentary structures that become evident approximately a billion years after the Big Bang (see PHYSICS TODAY, March 2007, page 20). The opening image illustrates how clusters of galaxies are found at the intersections of those filaments, which have a continuing infall of both dark and baryonic matter that fuels the clusters' growth. In fact, those clusters are the largest gravitationally bound systems in the universe today, with characteristic sizes of a few megaparsecs (Mpc) or about 10^{20} km.

The opening image belies the sometimes violent and very long time-scale motions present as a cluster evolves over billions of years. A sped-up view would reveal a stormy mélange of interactions between the cluster's diffuse plasmas, galaxies, and dark matter.

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The challenge is to re-create that evolution from sparse snapshots at different wavelengths.

Storm chasing

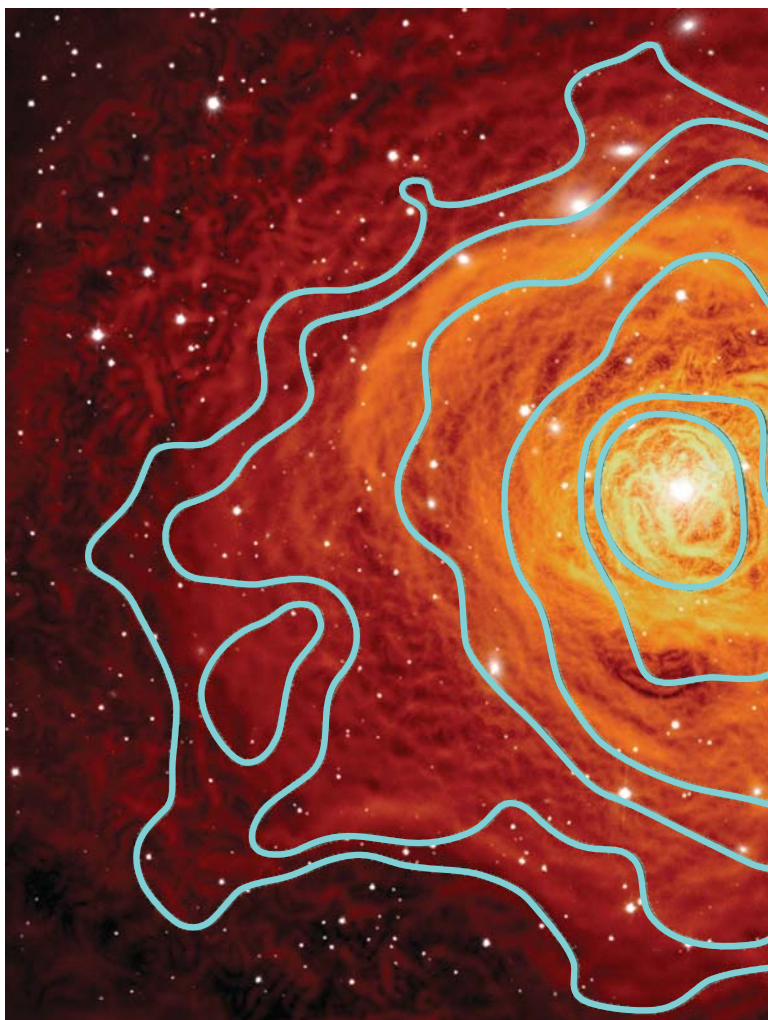
Clusters evolve relatively simply at first as material begins to fall into them, but shocks and other features soon develop in the diffuse plasma of the ICM. With densities of only $10^{-24}/\text{m}^3$, the ICM has an enormous particle mean free path of about 10^{17} km. In that extreme “collisionless” plasma, which is not seen anywhere on or near Earth, interactions are driven by plasma wave scattering. With its high ratio of plasma to magnetic field pressures, the ICM plasma provides bountiful opportunities to investigate interesting questions far beyond the reach of a terrestrial lab: Which types of plasma waves dominate? How do plasma structures transfer energy to different spatial scales? How can ions and electrons reach equilibrium with each other? How do magnetic fields and cosmic rays co-evolve?³

The radiative processes of two cluster-wide plasmas help astronomers reconstruct the history of the cluster. The x-ray-emitting ICM plasma reveals itself through free-electron collisions with ions (thermal bremsstrahlung); the radio-emitting cosmic-ray plasma shows itself through synchrotron radiation generated when relativistic electrons spiral around a magnetic field. The ICM also creates distortions in the cosmic microwave background spectrum that can help in diagnosing ICM properties. The cosmic microwave background photons first pass through the cluster. On their way to Earth, they experience inverse Compton scattering off hot electrons in the thermal plasma. The mechanism, known as the thermal SZ effect, was named for Rashid Sunyaev and Yakov Zel’dovich, who first described it⁴ in 1972. Magnetic fields provide yet another diagnostic tool, since they regulate the brightness and polarization properties of the synchrotron radiation. With typical strengths of 0.1–1 nT, the magnetic fields physically couple the thermal and relativistic plasmas and influence both the transport of heat in the ICM and the energization of the cosmic rays.

All those processes reveal different aspects of the plasmas, which astronomers use to determine densities, temperatures, the presence of shock waves, and other transient features in the ICM. They would love to watch the time-lapse maps of the radio and x-ray emissions to chart the passage of shocks and the generation and dissipation of turbulence. Unfortunately, the crossing time for clusters can approach a billion years, a bit beyond the typical astronomical career. But fortunately, weather vanes in clusters form when low-density and usually bipolar jets of plasma are ejected from supermassive black holes at the centers of some galaxies, the so-called active galactic nuclei. Those jets are deflected and distorted in their relative motion through the ICM and provide important insights into the dynamics of the thermal ICM plasma.

Gentle storms

Clusters have been growing over the past 10 billion years through the continuing infall of material, mostly clumps of dark matter, primarily along the filamentary structures. In some clumps, the accompanying baryonic matter has cooled sufficiently for stars and galaxies to form. Once those relatively compact galaxies reach the denser environment of the cluster cores, they are scattered by local irregularities in the gravitational potential. That process will eventually lead to an isotropic



distribution of orbits and a situation known as “virial equilibrium,” where the galaxies’ average kinetic energy equals one-half the magnitude of their average gravitational potential.

But for the infalling baryons still in a diffuse state, a quite different fate is in store. The high kinetic energy from their gravitational infall is converted into thermal energy in the outskirts of the cluster, which slows the infalling material’s velocity. That conversion happens at the so-called accretion shock, which causes a jump in density and temperature. Those shocks have been seen in computer simulations but not yet in observations. After conversion of its kinetic energy, the plasma—part of the ICM now—reaches a temperature of about 10^8 K, hot enough for astronomers to detect its radiation in x rays. As the stars in the cluster galaxies continue to age, winds and shocks transport stellar-processed material into the ICM, enriching it with elements, from carbon to iron, produced inside stars.

If that infall continues at a slow pace and without colliding with another massive system, the cluster can reach a relaxed state. While the higher-density galaxies approach virial equilibrium, the diffuse ICM reaches hydrostatic equilibrium, where gravity balances the gas pressure. Under those gentle conditions, a massive central galaxy 10^{13} times the mass of the Sun ($M_\odot$) can form with a supermassive black hole at its core. In the cluster’s inner regions, the radiative cooling time for the ICM is shorter than the age of the cluster, so central regions actually become colder than the diffuse medium farther out. Such relaxed clusters have high x-ray luminosities due to their high

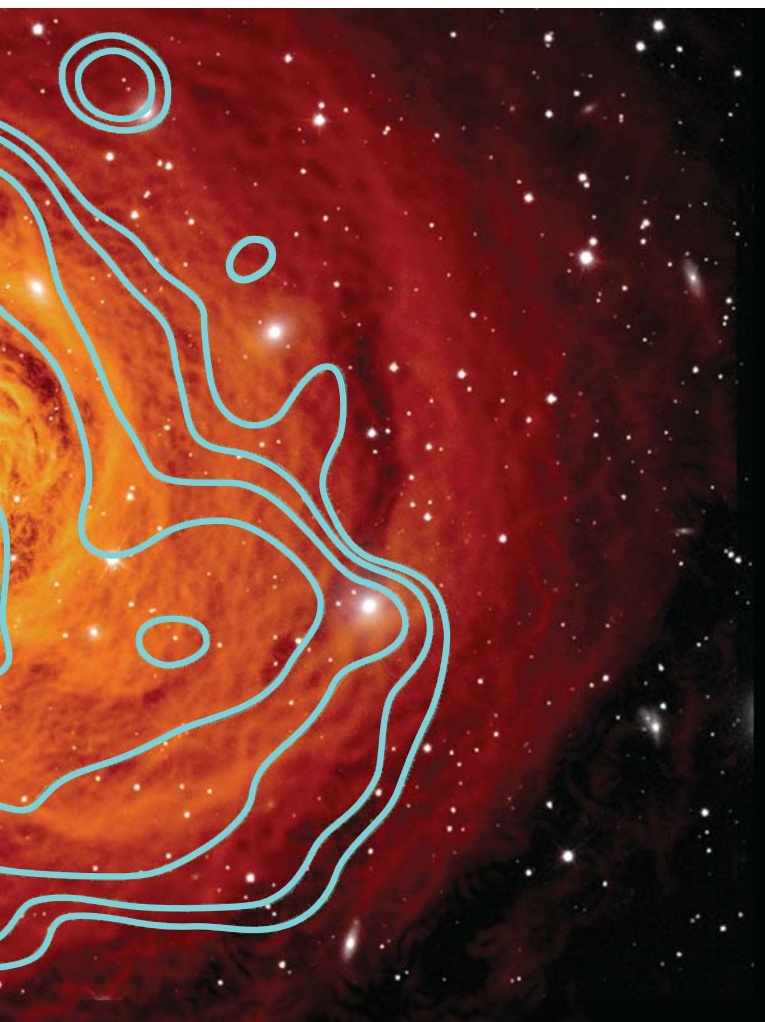


FIGURE 1. WHEN A MASSIVE COLD CLUMP of baryons and dark matter grazed the central region of the Perseus cluster, spiral-shaped ripples formed in the intracluster medium (ICM; orange, filtered from x rays). The image covers 400 000 parsecs; courtesy of Stephen Walker, NASA's Goddard Space Flight Center. The bright white patches show starlight from the cluster galaxies; they were observed with a 660 nm wavelength image from the Sloan Digital Sky Survey. Contours outline the corresponding synchrotron radiation from the relativistic plasma; courtesy of Marie-Lou Gendron-Marsolais, University of Montreal.

central densities. They are prominent in cluster surveys, where they are recognized by their bright, central x-ray cores, their Gaussian distributions of galaxy velocities, and their generally symmetric appearance.

That apparent cluster relaxation can be deceiving. If the smooth component of the cluster x-ray emission is filtered out, a new level of complexity reveals itself (see figure 1). The ripple structures arise when the infalling clumps of gas contain a substantial fraction of the cluster mass. Infalling material cannot be heated quickly enough, and a relatively cold (about 10^7 K) clump can penetrate deep into the cluster. The cold clump may also generate a bow shock that heats the surrounding medium. If the intruder is massive enough, it can even set off sloshing motions in the ICM baryons and produce spiral waves. Those sloshing motions can help mix the cooler and hotter gases, redistribute elements throughout the cluster, and induce turbulence that eventually dissipates the energy into heat.

The Perseus cluster, seen in figure 1, provides a dramatic example of sloshing motions in the ICM. And the likely culprit is an off-center encounter with a $10^{14} M_{\odot}$ clump approximately 2.5 billion years ago. Some of the energy also transferred into the cosmic rays, and the resulting synchrotron mini-halo is shown in the figure as cyan contours. Buried deep in the central galaxy NGC 1275, but not visible here, is also an active galactic nucleus, an accreting supermassive black hole. Its ejections evacuate bubbles in the x-ray emitting gas that may be seen as dark patches in the rich ICM structure.

Violent storms

When astronomers are lucky, they can catch one of the rarer major collisions between clusters of comparable mass. The Bullet cluster, seen in figure 2, shows the dramatic results of an encounter of greater than 10^{57} joules. The brightest, pink regions illuminate cooler ICM material from the original cluster cores. As the clump on the right passed through the preexisting ICM, it generated a pressure-matched, bow-shaped structure and beyond that, fainter, shock-heated regions. The diffuse plasma bore the brunt of the energy dissipation, while the cluster galaxies and dark matter had small enough cross sections that they passed through each other.

Looking at the synchrotron emission from cosmic-ray electrons and magnetic fields reveals additional information about stormy, multicluster mergers. Figure 3 shows the x-ray and radio synchrotron emission from the cluster Abell 2256, which likely formed—and is still forming—from the collision of two or three clusters. A few sharp edges in the x-ray emission reveal where cooler and warmer ICMs meet and create pressure-matched jumps in density and temperature; the x-ray emission otherwise appears mostly smooth. Likewise, the contours enclose an apparently smooth and faint region of radio synchrotron emission, called a radio “halo,” coincident with the x rays. The smoothness, however, is an illusion, limited by imaging capabilities and the unavoidable averaging of the emission along each line of sight through the cluster. Cosmic-ray electrons will radiate away their energy in only about 10^8 years, which is far shorter than the time they need to diffuse across the cluster. Therefore, their energy must constantly be replenished throughout the cluster volume by some underlying flow structures in the ICM.

That energy is thought to be supplied by a great deal of turbulence throughout the ICM that not only accelerates the cosmic-ray electrons but also amplifies the ICM magnetic field. Looking beyond the central regions, the source of energy powering the dramatic filamentary synchrotron feature, shown in green in the upper right of figure 3, remains unclear. Although the energy source may be associated with shocks generated in the cluster-forming collisions, the corresponding x-ray features have not yet been seen.

When shock structures can be simultaneously detected in the two plasmas—radio and x-ray emitting—then astronomers can use that information to reveal the energetics and dynamics of the cluster merger. A textbook example of such x-ray and radio shocks is seen in figure 4, from the so-called Toothbrush cluster. Such shocks are often found on the periphery of cluster x-ray emission and are termed “radio relics” for historical reasons. Shocks can be described most simply by their Mach number, the ratio of their advance speed to the local sound speed.

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Both the x-ray and radio shock features provide a way to estimate the Mach number, and their comparison helps astronomers determine whether they got the physics right. In the x rays, the jumps in density, temperature, or both are measured between the preshock and postshock material to calculate the Mach number. Astronomers must be mindful of uncertainties from limited spatial resolution and from averaging of emission along the line of sight. With these caveats, the discontinuity in the x-ray intensity profile shown on the right in figure 4 suggests the shock is quite modest, with a Mach number of about 1.3.

Because astronomers do not observe the radio preshock emission, they can't use the same kind of diagnostics to estimate the shock Mach number as they do for the x rays. However, astronomers know that cosmic rays can be energized at shocks, as is seen in solar flares. In a simple, idealized model of shock acceleration, often called diffusive shock acceleration, the cosmic-ray population follows a power law in energy, $N(E) dE \sim E^{-s} dE$. The synchrotron spectrum can be used to infer the power-law exponent, s , which is physically related to the Mach number. Observations of the Toothbrush relic reveal that instead of the very low x-ray-derived Mach number, the synchrotron-derived value is about 3.5. To first order, it's reassuring that those simple theories with very different underlying physics for interpreting the radio and x-ray observations both lead to low Mach numbers. But at second order, the discrepancies have led astronomers to look deeper at the uncertainties in both our observations and models.

Looking back at figure 3, another indicator of the hidden, large-scale flows in the ICM comes from the appearance of individual radio galaxies, shown in yellow with green tails. In those systems, oppositely directed jets of relativistic and thermal plasmas are ejected from supermassive black holes at the galaxy centers. As the jets encounter the ICM, they can be swept back by relative motion between the galaxy and the ICM. That relative motion gives the radio galaxy a tadpole-like appearance. And other bends and distortions to those radio tails provide a direct indication of otherwise invisible bulk motions in the ICM. Such distortions are sometimes spotted by astronomers in detailed studies of individual clusters. Sharp-eyed citizen scientists also help find those plasma-motion indicators by visually inspecting hundreds of thousands of images in projects such as Radio Galaxy Zoo.

The physics beneath the weather

One especially interesting and unanswered question arises from the radio synchrotron emission: What are the mechanisms by which the shocks and turbulence in the thermal plasma transfer energy to a small but highly energetic population of cosmic rays? The answer appears to lie in the smallest scales of the turbulence, where repeated scattering of electrons by self-excited and other magnetohydrodynamic waves slowly restores the energy that radiated away. Simultaneously, the magnetic fields required for synchrotron radiation start at very weak strengths as the cluster starts to form by processes that are currently unknown. Then shear motions in the turbulent ICM stretch the embedded fields and strengthen them by large

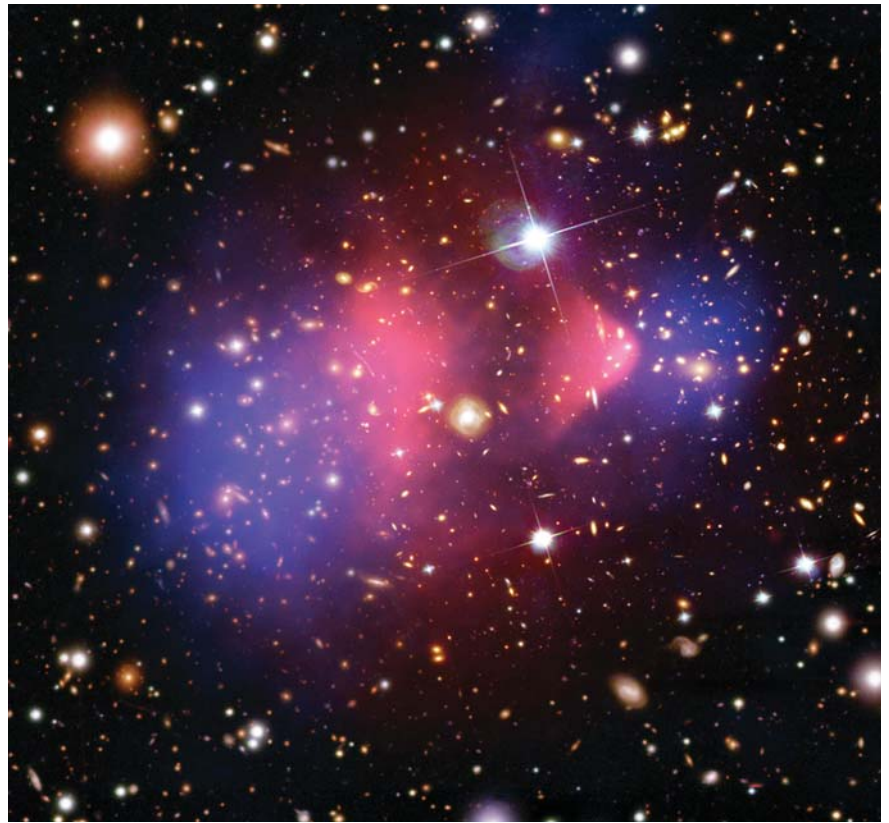


FIGURE 2. THE BULLET CLUSTER. X rays (pink) illuminate what remains of the intracluster mediums (ICMs) after a two-cluster collision. The clump on the right—one of the cluster's original, dense ICM cores—now generates a pressure-matched, bow-shaped feature in the surrounding ICM. The small cross sections of the galaxies (white) and dark matter (blue) allowed them to pass through each other with no interaction. (X ray: NASA/CXC/M. Markevitch et al. Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al. Lensing map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe et al.)

factors. A better understanding of such a complex set of interconnected processes requires numerical simulations.

But numerical simulations of cluster plasmas face huge challenges. They need to start with two large-scale phenomena: the inflows of magnetized thermal plasma that originate during cluster formation and the more dramatic merging of clusters. At the same time, simulations must incorporate how turbulent energy dissipates on the smallest scales, far below the resolution of cluster-wide numerical simulations. Processes such as Alfvénic, compressive, solenoidal turbulence, and cosmic-ray self-excited modes are under intense study.⁵

Another important question that the simulations try to answer concerns the origin of the radio synchrotron emission: Where may a seed population of lower-energy electrons be obtained so that shocks can further accelerate them, as required by existing observations? One possibility is that the seed electrons belong to the 10^{-8} K ICM. However, the low Mach number shocks found in theoretical work and inferred from some x-ray observations appear insufficient to provide the necessary acceleration. Another possibility is that the shock is fed by a preexisting population of relativistic electrons left behind by old radio galaxies. That approach looks promising, although the devil is in the details. Other mechanisms, such as shock drift acceleration need to be explored, and more



FIGURE 3. THE ABELL 2256 CLUSTER, generated from a multiple cluster merger, shows a rich variety of structures. Purple indicates the 2–10 keV x-ray emission from the intracluster medium (ICM). Orange shows the starlight from cluster galaxies in the near-IR band. Radio synchrotron emission from cosmic-ray electrons is displayed in green, and the contour indicates the extent of the diffuse synchrotron “halo.” Yellow indicates a few of the cluster galaxies with supermassive black holes, whose radio jets have been distorted by relative motion through the ICM. (Adapted from ref. 6.)

combined x-ray and radio spectral diagnostic cases, along with advanced numerical simulations, will be required to sort out those issues.

The eye of the storm

Deep in the cores of relaxed clusters, ones that haven’t been perturbed by a major merger in billions of years, another prob-

lem is brewing. In such a high-density region, the x-ray radiative cooling times of the hot ICM are short enough that hundreds to thousands of solar masses of material should be forming new stars each year (see the article by Christoph Federrath *PHYSICS TODAY*, June 2018, page 38). Instead, observations indicate that only tens of solar masses’ worth of stars are turning on each year. Some other cooled material, independently found at millimeter wavelengths, also falls far short of the expected amount of cooled mass.

The gain or loss of heat from the ICM cannot be measured using only the temperature, T , since both T and the local density, n , can be changed by adiabatic processes. Instead, cluster astronomers define the entropy-like quantity $K = T/n^{2/3}$, which will change only when the ICM gains or loses energy. For simple but plausible scenarios of cluster formation, the expected variation of $K(r)$ can be calculated, where r is the distance from the cluster center. In the case of successive accretion onto a cluster whose mass is steadily increasing, the expected profile is $K(r) = K_0 r^{1.1}$, close to what is observed beyond the cluster cores. In the cores, however, the entropy drops more slowly

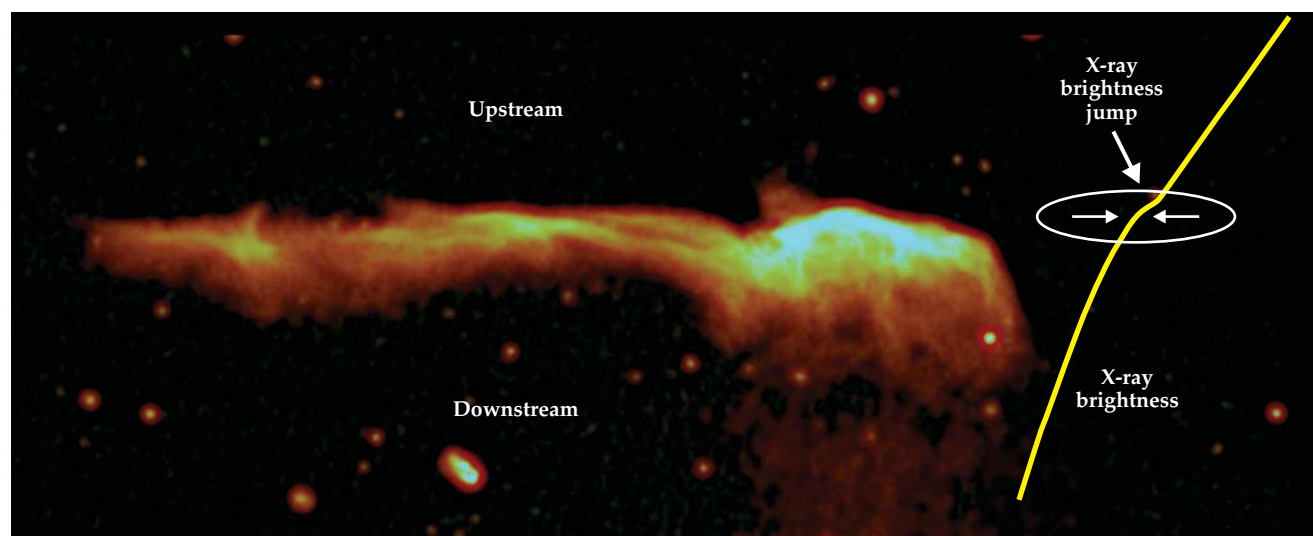


FIGURE 4. RADIO EMISSION FROM THE TOOTHBRUSH CLUSTER illuminates an upward-moving shock at the northern edge of its parent cluster. A profile of the x-ray emission along a vertical line through the brightest radio region from the downstream (postshock) to upstream (preshock) material is shown sideways on the right. A brightness discontinuity, the x-ray signature of a shock, can be seen at the same location as the radio emission feature. (Adapted from ref. 7.)

closer to the center, a trend that requires some additional input of heat to the ICM.

One likely source could be episodic ejections of relativistic plasma jets from the supermassive black hole in the bright central galaxy. Figure 5 shows the red synchrotron lobes from a radio galaxy that injected approximately 10^{55} J and excavated enormous cavities in its surrounding ICM. The work done by such outbursts and by cosmic-ray heating and sloshing motions in the ICM appears sufficient to balance the cooling. Clusters may therefore self-regulate over billions of years, and the infall of material onto the central supermassive black hole may be controlled by the cooling and instabilities near the cluster core, which are themselves controlled by the energy released from the emerging jets.

Naively, astronomers might have expected that those dense cluster cores had reached a quiet equilibrium state, even while the cluster outskirts continue to be perturbed by infalling material. But observations suggest the multiphase plasmas in cluster cores have their own complex dynamics full of interesting astrophysics and new challenges.

The weather forecast

Astronomers very much want to discern the bulk motions in the ICM. In its far too brief 38 days in space, the Japanese x-ray satellite *Hitomi* gave a taste of things to come. With its exquisite spectral resolution, *Hitomi* directly measured the Doppler line broadening and centroid shifts of the lines from highly ionized iron in the core of the Perseus cluster. At 100–200 km/s, the observed velocities provided the first direct measurements of the streaming and random gas motions in the central regions of a cluster ICM. They also reflected energy inputs from both gravity and the jets from the supermassive black hole. While discovering those exciting signposts of ICM activity, *Hitomi* also confirmed that the ICM is still quite close to hydrostatic equilibrium.

Astronomers are eager for new instrumentation. On the x-ray side, eROSITA, a joint German–Russian venture, is projected to characterize the ICM in 50 000 to 100 000 clusters up from the current tally of approximately 2000. The haul will dramatically expand the capacity for statistical and cosmological studies. The exquisite spectral resolution and sensitivity of *XRISM*, a joint Japanese–US mission, will map out the details of velocity structures in the ICM. Further down the road, the European satellite *ATHENA* will allow us to study the history of how the ICM is heated and chemically evolves over cosmic times. Likewise, NASA is considering the *Lynx* mission, which could probe the diffuse medium in cluster-feeding filaments down to the astonishing low value of about 7 atoms/m³.

Complementing those studies are a new generation of radio telescopes and surveys. At low frequencies, the LOFAR Two-Metre Sky Survey and the Murchison Widefield Array have begun to reveal the extensive cluster synchrotron structures that are no longer visible at high frequencies because of radiative energy losses. Polarization at low frequencies and the new very wide bandwidth capabilities at the Very Large Array will provide detailed probes of magnetic field irregularities in the ICM. And large area surveys using polarization, such as the Very Large Array Sky Survey and the Polarisation Sky Survey of the Universe's Magnetism on the Australian Square Kilometre

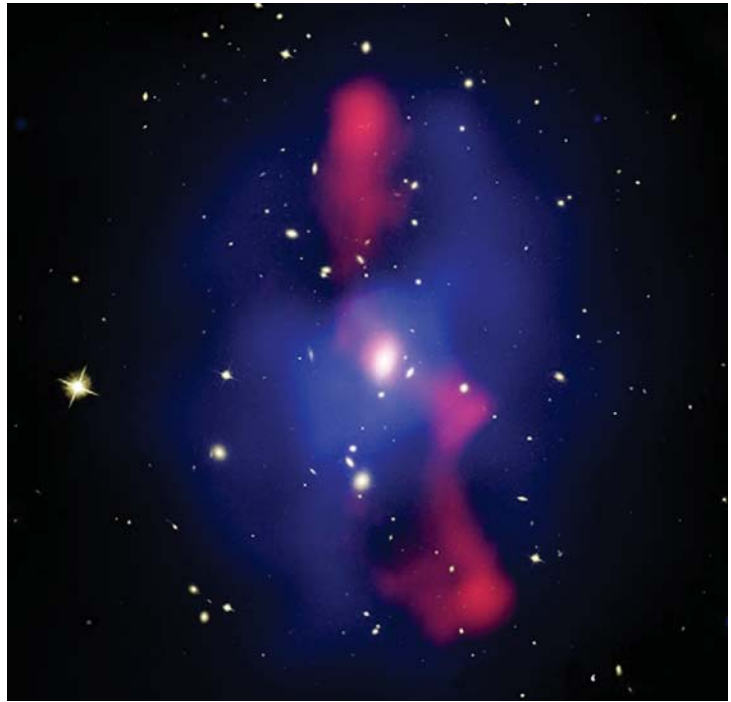


FIGURE 5. THE MS 0735.6+7421 CLUSTER. The cluster's inner 700 000 parsecs contain stars and galaxies observed at near-IR wavelengths around 800 nm (white) surrounded by the intracluster medium (ICM; blue), a thermal plasma seen in x-ray emission. The synchrotron emission (red) highlights the radio plasma that excavated cavities in the thermal ICM. (Adapted from ref. 8.)

Array Pathfinder telescope, will allow statistical studies to connect the magnetic structures in the ICM with other physical properties of clusters far beyond current capabilities. Yet another major leap will occur with the Square Kilometre Array itself.

Even more lies on the horizon. Detector technology has yet to reach the sensitivity needed to realize two other potentially powerful diagnostics: the x-ray inverse Compton radiation from the upscattering of cosmic microwave background photons by the cosmic-ray electrons, and the gamma rays expected from pion decay after they are produced by cosmic-ray and thermal proton collisions. But instrumentation is becoming ever more powerful and computer simulations increasingly sophisticated. The weather outlook for the ICM is both stormy and exciting!

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