Plasma physics in clusters of galaxies

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Abstract

Clusters of galaxies are the largest self-gravitating structures in the universe. Each cluster is filled with a large-scale plasma atmosphere, in which primordial matter is mixed with matter that has been processed inside stars. This is a wonderful plasma physics laboratory. Our diagnostics are the data we obtain from X-ray and radio telescopes. The thermal plasma is a strong X-ray source; from this we determine its density and temperature. Radio data reveal a relativistic component in the plasma, and first measurements of the intracluster magnetic field have now been made. Energization of the particles and the field must be related to the cosmological evolution of the cluster. The situation is made even richer by the few galaxies in each cluster which host radio jets. In these galaxies, electrodynamics near a massive black hole in the core of the galaxy lead to a collimated plasma beam which propagates from the nucleus out to supergalactic scales. These jets interact with the cluster plasma to form the structures known as radio galaxies. The interaction disturbs and energizes the cluster plasma. This complicates the story but also helps us understand both the radio jets and the cluster plasma.

I Overview

Clusters of galaxies that we see today have been built up by gravitational collapse of tiny density fluctuations in the early universe. The galaxies in the cluster swim in a sea of hot plasma. Because this plasma is easy to observe, and has been thought to be simple to interpret, it seems an attractive probe of the cluster structure, and thus cosmology. However, we need to understand the plasma before we can use it to study larger questions.

In this paper I review our current knowledge of the cluster plasma, with emphasis on areas of uncertainty and areas where input from other arenas of plasma physics will be particularly helpful. I will use astronomical length scales. One parsec (pc) is about 3 light-years. The diameter of a typical galaxy ~ 30 kpc. The length of a radio jet ranges from a few to a few hundred kpc. The diameter of a cluster core ~ 0.5Mpc, while the entire cluster extends out to $\gtrsim 2$ Mpc. An astronomical unit (AU) is the distance from the earth to the sun, ~ 5µpc. The gravitational radius of a massive black hole ~ $1 - 10$AU.

A Clusters of galaxies

Clusters of galaxies are the density maxima in the large-scale distribution of mass in the universe. The largest, brightest clusters are called “rich”; they are the easiest to study. Much of the gravitating matter in any cluster is “dark”, meaning it does not radiate in any detectable band; it is thought to be non-baryonic. Some of the luminous, baryonic matter formed the stars within galaxies; the rest remained as the diffuse plasma atmosphere of the cluster. This Mpc-scale plasma is easily detected with X-ray telescopes, and is commonly referred to as the Intra-Cluster Medium (ICM).

B Jets from galactic cores

A few galaxies within the cluster host Active Galactic Nuclei (AGN) in their cores. The combined action of gravity and angular momentum forces galactic matter into an accretion disk around a massive central black hole. Electrodynamics forces drive jets of relativistic plasma out from the disk. These jets, which begin on µpc scales, remain collimated while propagating to much larger scales (kpc to Mpc). They are most often detected by their radio synchrotron emission, thus are called “radio jets”. They usually escape their parent galaxy and interact with the local ICM. The beautiful structures formed when the jets interact with the ICM are called “radio galaxies”.

C The plasmas in this environment

In many ways the study of the cluster-wide plasma is still in its infancy. We are gathering data and trying to understand the basic physical state of the plasma. Much of the cluster plasma is well thermalized, obeying a Maxwellian distribution function (DF) at warm, but subrelativistic, temperatures. We know the plasma is magnetized, but as yet we know little about the strength or structure of the field. The plasma may also contain a relativistic component, with a non-thermal DF, in which the internal energy
per particle is much greater than the rest mass. The study of radio jets is somewhat more mature. We know the jet plasma contains highly relativistic particles, again with a non-thermal DF. It is not clear whether it contains any cooler or subrelativistic component. The jet plasma is magnetized, probably at approximate equipartition levels. Current work in this field is aimed at understanding the energetics and stability of these well-collimated plasma flows.

II Diagnostic tools

This relatively new field is driven by data taken with radio and X-ray telescopes. These observations can be grouped into four types of diagnostics. All apply to the cluster plasma; only one or two apply to radio jets.

A Thermal X-ray emission

This is our main diagnostic for the cluster plasma. Several generations of X-ray satellites have enabled detailed study of the thermal component of the plasma.\(^1\)

Thermal bremsstrahlung from a plasma at density \(n\) and temperature \(T\) has emissivity,

\[\epsilon_{\text{brem}}(\nu) \propto n^2 g(\nu, T) e^{-h\nu/kT}\]  \hspace{2cm} (1)

where \(g\) is a slow function of frequency and temperature.\(^2\)

Broad-band X-ray images of nearby clusters are well resolved spatially, showing that most rich clusters are regularly shaped and quasi-spherical. Figure 1 shows an example. Straightforward deprojection of the data tells us the density structure of the thermal ICM. X-ray spectra can also be obtained, with moderate spatial resolution, revealing spectral lines from highly ionized heavy elements in addition to pure bremsstrahlung. From these data we determine the temperature and composition of the thermal ICM.

B Synchrotron emission

This is our main diagnostic for radio jets, which are bright enough that high quality images can be obtained with radio interferometers.\(^3\) Synchrotron emission from some jets can also be detected in the optical (and possibly X-ray) bands.

In addition, synchrotron emission has now been detected from the diffuse plasma in some clusters of galaxies.\(^4\) When this emission extends throughout the thermal ICM, and is called a “radio halo”. In other clusters, it sits on the edge of the cluster, and is called a “radio relic”; in still other clusters, the emission seems to be patchy and irregular relative to ICM.

What can we learn about the emitting plasma? Synchrotron emission comes from relativistic particles in a magnetized plasma. The emission from a single particle peaks at \(\nu \propto \gamma^2 B\). A useful way to write the emissivity is

\[\epsilon_{\text{sy}}(\nu) \propto B^{1/2} \nu^{1/2} n[\gamma(\nu; B)]\]  \hspace{1cm} (2)

if \(n[\gamma(\nu; B)]\) is the number of particles at energy \(\gamma\) which radiate at \(\nu\) in a magnetic field \(B\). Thus, detection of diffuse synchrotron emission is a direct detection of magnetic field and relativistic electrons.

Two details will be useful below. If we assume the usual power-law electron DF, \(n(\gamma) \propto \gamma^{-s}\), we find a power-law radiation spectrum: \(\epsilon_{\text{sy}}(\nu) \propto \nu^{-(s-1)/2}\). If we further assume \(s \approx 3\), which is typical of cluster radio haloes, we find \(\epsilon_{\text{sy}}(\nu) \propto P_{\text{rel}}P_B^{-1}\). The emissivity in this case depends on the product of the pressures in relativistic particles and field.

C Faraday rotation

Polarized synchrotron emission from radio galaxies in clusters allows us to measure the magnetic field in the plasma between us and the galaxy.

The different phase speeds of right-hand and left-hand polarized signals, in a magnetized plasma, result in rotation of the plane of linear polarization as the signal propagates through the plasma. The polarization angle

Figure 1 The regular cluster A2163. Contours are from the X-ray image, showing the distribution of bremsstrahlung from the hot, thermal plasma. False-color image\(^5\) is the radio emission, showing diffuse synchrotron from the relativistic, magnetized component of the plasma. The bright radio spots are individual cluster galaxies or background sources. The scale of the image \(\sim 1\) Mpc. X-ray data from the ROSAT archive.
\[ \chi \text{ rotates by } \quad \frac{d\chi}{d\lambda^2} \propto \int nB \cdot dl \quad (3) \]

Because of the algebraic sign in the inner product, and the possibility of an \((n, B)\) anticorrelation, the integral in (3) can be much smaller than the simple product \(n|B|l\). Thus, detection of Faraday rotation is a detection of magnetic field, but the converse does not hold.

If the plasma responsible for the Faraday effect is separate from the emission source, the signal will obey \(\chi \propto \lambda^2\); if the radio-loud plasma itself causes the rotation, the simple \(\lambda^2\) behavior will be lost. Faraday measurements of radio galaxies within or behind clusters of galaxies usually show the clear \(\lambda^2\) behavior, supporting their use as probes of the ICM.

Radio sources in clusters generally have larger Faraday rotation than those not in clusters. Imaging studies of embedded sources find the rotation is ordered, not random, with order scale \(\sim 3 - 30\) kpc. High rotation is detected from the dense, central “cooling cores” (see below), while lower rotations are found from sources in lower density environments.\(^5\)

D Nonthermal X-ray emission

X-ray spectra of the ICM show a hard X-ray (HXR) “tail” on the thermal bremsstrahlung spectrum. This has only been confirmed for a few clusters,\(^6\) but detecting such a faint signal is difficult even with the new X-ray instruments available. In addition, extreme-ultraviolet (EUV) emission has been reported from several clusters, but these are also difficult observations, and the detections remain controversial.\(^7\) The paucity of captured HXR or EUV photons has not, however, inhibited modeling and speculation on the nature of this emission.

The most attractive explanation is that this high-energy emission arises from inverse Compton scattering (ICS) of microwave background photons (relic radiation from the very early universe, now cooled to 2.7K) by relativistic electrons. The emission from a single particle peaks at \(\nu \propto \nu_o^2\), if \(\nu_o\) is the frequency of the incoming photons. The ICS emissivity per particle, in a radiation field with energy density \(U_{rad}\), can be written,

\[ \epsilon_{ics} \propto U_{rad}(\nu_o,\nu)^{1/2} [\gamma(\nu;\nu_o)] \quad (4) \]

As with synchrotron, if we assume \(n(\gamma) \propto \gamma^{-s}\), we again get a scattered power law: \(\epsilon_{ics}(\nu) \propto \nu^{-(s-1)/2}\). Because \(U_{rad}\) is fixed, detection of ICS from a cluster is a direct detection of relativistic electrons in the cluster plasma.

III The intracluster plasma

From the X-ray luminosity and spectra, we know that the ICM is dominated by a hot, thin maxwellian plasma, at \(n \sim 10^{-4} - 10^{-3}\text{cm}^{-3}\) and \(T \sim 10^7 - 10^8\)K. It is almost all hydrogen, with heavier trace elements at approximately half solar abundance. The temperature and composition are approximately uniform throughout the cluster, with only small spatial variations. The density is centrally enhanced, with a central core radius \(\sim 0.1 - 0.3\) Mpc, and falls off at larger radii, as \(\propto r^{-2}\) or faster. The cluster A2163 in Figure 1 is a good example.

From the composition of the ICM we infer its origins. The very lightest elements (H, He, and very small amounts of Li and Be) are primordial — relics of nuclear reactions in the very early universe — while the heavier elements are created inside stars. It follows that about half of the ICM is primordial, having taken part in the original gravitational collapse of the dark matter. The other half of the ICM must have been processed by stars in the cluster galaxies. Massive stars are short-lived, and at death recycle most of their mass to the interstellar medium in their galaxy. Much of this material must have been stripped or ejected from the galaxies, and joined the diffuse ICM, in order to account for the current chemical composition of the cluster plasma.

A Dynamical state

It was initially thought that clusters of galaxies are static, self-gravitating systems, decoupled from the larger scale universe. We now know this is only approximately true; but it is still useful as a “zero-order” description.

Most rich clusters have smooth, centrally concentrated distributions of gas and galaxies within the cluster core. The thermodynamics of the ICM seem simple. It was heated in the initial gravitational collapse of the cluster. Lacking present-day heating sources, the ICM remains at that temperature today because radiative losses are unimportant over the life of the cluster. The dynamical state of the ICM also seems very simple. The dark matter determines the gravitational potential. The ICM sits in hydrostatic equilibrium in the potential well of the dark matter:

\[ \nabla^2 \Phi = 4\pi \rho_{\text{dark}} ; \quad \nabla p_{\text{icm}} = -\rho_{\text{icm}} \nabla \Phi \quad (5) \]

Simple solutions to the first equation show a characteristic core radius of the gravitating matter, which depends on its central density and internal energy. Simple solutions to the second equation find the core radius of the dark matter is also the core radius of the cluster plasma.

1 Cooling cores

An interesting subset of rich clusters deviate from this simple picture; they have an unusually dense central concentration of plasma. Radiative cooling is important in these cores. Unless there is ongoing heating, the central
gas should be quite cool. In addition, the simple system (5) no longer describes the central ICM. Instead one expects radiatively regulated inflow, with the gas slowly settling into the center as its pressure support is lost. Simple models predict typical inflows of several hundred solar masses per year in strong cooling cores.9

This overly simple picture has not been supported by observations.10 Extensive searches have failed to find the large amount of cooled matter predicted to have accumulated in the cores (either as cold plasma or as recently formed stars). In addition, we now know that radio-loud AGN exist in almost every cooling core; their jets may be important in heating the central ICM and offsetting the radiative losses.

2 Mergers: flows, shocks and cool fronts

We now know that clusters are still evolving, as small and large clumps of matter continue to merge with the system. We believe minor mergers are common in most clusters at the present time. Many clusters show subtle signs of this, such as bimodal galaxy distributions, or small irregularities in the plasma distribution. Simulations11 show that large-scale bulk plasma flows and small-scale turbulence should be common; unfortunately these are hard to measure directly.

A few clusters are undergoing major mergers, in which two mass clumps of comparable size are merging at the present day. These have clear observational signatures. Perhaps the most striking are the large, peripheral shocks created when the two clumps hit supersonically. A2256, shown in Figure 2, is a striking example. The shock can be seen in the X-ray image as a bright, transverse feature on the edge of the cluster. Temperature maps show this feature is hotter than the rest of the cluster plasma.12 Radio maps show this feature is bright in synchrotron emission (see below), and that its magnetic field is ordered, parallel to the bright emission ridge13,14. Both results support the identification of this structure as a very large (∼ 0.5 Mpc) plasma shock.

Recent X-ray data reveal new, quite unexpected features, now called “cool fronts”.15 Some merging clusters contain very thin, large-scale contact discontinuities, unresolved at a few kpc, between cool and warm plasma. Their concave shape initially suggested a bow shock, but the sign of temperature jump was found to be wrong. Plasma behind the front turns out to be cooler, not hotter, than that ahead of the front. These are now believed to be due to subsonic mergers, in which the cooler core of one cluster is moving through warmer gas in another cluster, rather like slow fluid flow around a smooth rock.

Figure 2 A2256 is an example of a merging cluster. False-color shows radio synchrotron emission from the nonthermal component.14 Contours show X-ray emission from the thermal plasma. The thermal plasma shows some distortion, to the upper right, where the plasma is hotter. The radio emission, however, reveals a large, offset feature which is thought to be a shock created by the merger. A fainter radio halo, central to the cluster, can also be seen, as well as individual radio galaxies within the cluster core. The scale of the image ∼ 1 Mpc. X-ray data from the ROSAT archive.

B Magnetic field

We are learning that the ICM is magnetized, as we detect both synchrotron emission and Faraday rotation from the plasma. Unfortunately, neither diagnostic allows clear determination of the strength or structure of the cluster field.

1 Derived from radio haloes

Diffuse synchrotron emission traces both the magnetic field and relativistic particles in the ICM. The intensity of the radiation depends on both components; without additional information we cannot determine the energy density in the field or the particles. One common approach in radio astronomy is to minimize the total nonthermal pressure ($p_{rel} + p_B$), subject to the constraint of the observed emissivity (as in equation 2). Because this analysis leads to comparable field and particle energies, it is called “equipartition”. If HXR emission is also detected from the cluster, its strength can be used to find the relativistic electron density (from equation 4), allowing the field to be determined from the synchrotron emission. When a uniform, homogeneous magnetic field is assumed, both methods tend to find $B ∼ 0.1 − 0.5 \mu G$.16

Radio halo observations provide only indirect information on the field structure. Although synchrotron emis-
sion from a uniform magnetic field is highly polarized, the haloes are unpolarized. It follows that several field reversals must occur along the line of sight within the cluster, or transversely within the resolution of the observations. From this we can infer the field order scale is no larger than \( \sim \text{tens of kpc} \).

2 Derived from Faraday rotation

In order to use Faraday data to measure the cluster field, one must know the structure of the field and the degree to which it mixes with the cluster plasma (equation 3). Most work has made the simplest assumption, that the cluster field is disordered, space-filling and well mixed with the thermal ICM. It is also common to identify the order scale apparent in the RM images, \( \sim 10 \text{ kpc} \), with the order scale of the magnetic field. This approach finds fields \( \sim \text{few } \mu \text{G} \) throughout the cluster core, and higher fields (tens of \( \mu \text{G} \)) in the dense cooling cores.\(^{17,18}\)

However, it is not clear if the magnetic field inferred from RM data reflects the field throughout the cluster. There may be a boundary layer in which magnetic field carried out by the radio jet mixes with the ICM. In addition, the radio jet will deposit energy to the local plasma, thereby driving turbulence and amplifying smaller, seed fields there. If either of these effects is important, the rotation measures may not be typical of conditions throughout the cluster. Statistical studies of radio sources behind (not inside of) clusters could in principle detect “uncontaminated” cluster field, but such studies have so far have been inconclusive.\(^{18,19}\)

C Relativistic plasma

We are learning that the ICM can contain a significant fraction of highly relativistic particles; in some clusters we have detected synchrotron and HXR emission from these particles. We do not yet know how common, or how significant, this component is in all clusters.

1 A significant component?

As yet we know very little in detail about this relativistic plasma. We do know that electrons at Lorentz factors \( \sim 10^3 \rightarrow 10^4 \) are required to account for the synchrotron emission, and also to produce the HXR emission from Compton scattering of the microwave background. The electron DF is not known with certainty. By analogy to galactic cosmic rays and to radio jets, the particle DF in the haloes is often assumed to be a power law, \( \text{with an unknown low-energy cutoff} \). The energy density of the relativistic electrons is at least a few percent of that in the thermal plasma, in clusters with detected HXR. It could be larger if the low-energy cutoff is chosen less conservatively. We have no information on relativistic ions in the cluster plasma. Galactic cosmic rays contain \( \sim 100 \) times more energy in baryons than in leptons. If this is also true for the cluster, the relativistic component of the plasma is indeed important energetically.

2 A universal component?

It is not yet clear if the ICM in every cluster has a strong relativistic component. Because very few haloes or relics were initially detected, they were thought to be rare. If this is the case, they must be due to an unusual recent event in the cluster’s life, such as a major merger. On the other hand, more haloes are being found, and the data available at present hint at a correlation between synchrotron and X-ray power in rich clusters.\(^{3,20}\) If this trend is verified when more data become available, it strongly suggests that the nonthermal component is common to all clusters, and probably simply a by-product of cluster “weather”. Our uncertainty reflects the fact that the observations necessary to detect diffuse synchrotron emission from the cluster plasma are difficult and time-consuming; they are only beginning to be carried out systematically.\(^{21}\) We must wait a few years, until work currently underway has been carried out, before we can say whether diffuse synchrotron emission is common to all rich clusters, or is found only in a special few.

3 Origins and energization

If radio haloes and relics turn out to be common, then the relativistic electrons have a lifetime problem. Their radiative lifetime (to ICS on the microwave background) is about one percent of the age of the cluster. Because radio haloes extend throughout the cluster volume, their electrons cannot have been injected or accelerated at some special point in the cluster (such as an active galaxy or a large-scale merger shock). Their diffusion rate is too slow, and for electrons is limited by the radiative lifetime; we would expect the radio emission to be localized around the injection point. Thus, relic sources may be due to one localized event, but halo sources cannot be. The electrons in radio haloes must be undergoing \textit{in situ} energization in the diffuse cluster plasma.

D An example: the Coma cluster

There are not yet enough well-measured halo clusters to draw broad conclusions about the nonthermal plasma. We can, however, look at one nearby, well-studied object. The thermal plasma in the Coma cluster has a smooth, regular structure. Its core has radius \( \sim 300 \text{ kpc} \), \( n = .003 \text{cm}^{-3} \), \( T \sim 9 \times 10^7 \text{K} \). It has detected HXR emission (whose spatial extent is unknown). It has a smooth radio halo, extending throughout thermal gas.
Radio galaxies within the core have Faraday rotation values typical of other rich clusters, although sources in this cluster have not been studied in as much detail as elsewhere.\textsuperscript{17,18,23}

The simplest model of the ICM in Coma would be a uniform, space-filling magnetic field, fully mixed with the thermal and nonthermal plasmas. With this assumption, one can determine $B$ from the ratio of ICS to synchrotron power (equations 2 and 4): the result is $B \sim 0.2 \mu G$. This disagrees, however, with the Faraday data. If the field has an order scale $\sim 10$ kpc (consistent with other Faraday studies and the lack of polarization), and is well mixed with the thermal plasma, we need $B \sim 2 \mu G$. This factor of ten discrepancy is unsatisfying (even in astrophysics), and suggests the model is wrong. In fact, the uniform, space-filling magnetic field is physically unlikely. We know magnetic fields elsewhere (such as turbulent or space plasmas) are inhomogeneous, with high-field, high-current filaments, placed intermittently throughout a lower-field region\textsuperscript{24}.

Consider, therefore, a two-phase plasma as our toy model. Let high-field flux ropes be surrounded by low-field interfilament regions, with the two phases in pressure balance. We want the filaments to have a covering factor at least unity (so that any line of sight will show Faraday rotation). The volume filling factor must be $\sim 0.1$–0.5 for the length scales (10 & 300 kpc) used in this toy model. The filaments can account for the Faraday signal if they are internally magnetized, with $B \sim 30 \mu G$ and $p_{th} \ll p_B$ inside the filament. Only a small fractional pressure in relativistic electrons is required also to account for the radio halo. The HXR is dominated by relativistic electrons in the interfilament region. The minimum energy density needed there, to explain the HXR emission, is $\sim 1\%$ of the thermal plasma energy density. As discussed above, this value could be much larger.

\section{The plasma in radio jets}

Radio jets are well-collimated, relativistic outflows, which begin on black-hole scales (several \(\mu\)pc), and propagate to extragalactic scales. Bright features (waves or shocks) in the inner (\(\lesssim\) kpc) jet show high-speed outward motion, at bulk Lorentz factor $\sim 3–10$.

We detect jets by their synchrotron radiation. We therefore know they contain a magnetized, internally relativistic plasma. This radiation is strongly polarized, from which we deduce the field is well-ordered. This is our only diagnostic: there is no internal Faraday rotation, nor any compelling evidence as yet that the HXR seen from a few jets are due to ICS. High resolution images show the plasma is inhomogeneous, with luminous filaments that probably trace high-$B$ regions. There are hints that the plasma is mostly or fully relativistic, with no significant cooler, thermal component. Indirect arguments suggest the plasma is within a factor $\sim 10$ of equipartition between the magnetic field and relativistic electrons. The equipartition fields are typically $\sim 10 – 100 \mu G$ on kpc-Mpc scales, and larger in the galactic core.

Models of jet creation suggest even more extreme conditions might exist.\textsuperscript{25} Electromagnetic or MHD acceleration is the most likely close to the black hole. Such jets may carry a net current from the galactic nucleus out to extragalactic scales. The return path is not clear, but it is probably established through the interaction of the jet with the ambient plasma. Some models start with a strong Poynting flux jet; subsequent pair creation will produce an electron-positron jet. Alternatively, mass-loading by entrainment from the ambient plasma may turn these into electron-ion jets by the time we observe them on extragalactic scales.

\section{Energetics}

Two issues deserve mention here. How much energy does the jet deposit in the ICM? How does the jet convert flow energy \textit{in situ} to internal energy of the relativistic particles and magnetic field?

\subsection{Energy carried by the jet}

What energy does the jet carry? We can write it down easily enough:

$$P_j = \pi r^2 \gamma^2 \beta c \left( \rho c^2 + 4p + \frac{B^2}{4\pi} \right)$$

assuming an internally relativistic plasma and using ideal MHD. But $P_j$ can only be determined indirectly in most cases. The luminosity of the associated radio galaxy, which is easy to observe, is at best an indirect probe of $P_j$. It depends on the particle and field history of the source as well as current conditions in the jet. Nonetheless, estimates such as $P_{rad} \sim 10^{-6} P_j$ are common in the literature. Such estimates may be useful statistically, but they can hardly describe a single source at any given time. Going beyond this, some authors have invoked simple dynamical models of the larger radio source, for instance what $P_j$ must have been in order for the jet to propagate a given distance in a given time. Such estimates are unsatisfying because they rely on important issues which are hard to determine, such as source age or AGN duty cycle.

\subsection{Internal Energization}

Some of the energy flowing in the jet must be converted \textit{in situ} to relativistic particles and magnetic field. This is needed to offset both expansion and radiative losses.
The jets expand dramatically between their origin at the accretion disk and when they become observable as radio jets. They continue to expand, albeit more slowly, out to much larger, extragalactic scales. If the flow were adiabatic, the plasma would cool during the expansion and the B field would decay by flux freezing. The observations clearly contradict this: the synchrotron emissivity does not decay significantly going along the jet.26

Radiative losses are also relevant. If the magnetic field is not too far from the equipartition value, the radiative lifetime of the relativistic electrons is less than the travel time along the jet. This predicts a gradual steepening of the spectrum, going along the jet (as the particles lose energy), followed by a frequency-dependent end to the emissivity. This again contradicts the observations. Thus it seems very likely that in situ energization is taking place in radio jets on \( \gtrsim \) kpc scales.

B An example: M87

This galaxy, in the core of the Virgo cluster, is one of the closest AGN. Synchrotron emission from its jet (shown in Figure 3) has been detected in optical, radio and X-ray bands.27,28 What do we know about this jet?

![Image 3](image3.png)

**Figure 3** The jet in the nearby active galaxy M87, shown in a radio image from the VLA.27 The bright spot at left is coincident with the massive black hole in the galactic core. Most of the bright features show relativistic proper motions away from the core.29 The scale of the image \( \sim 1.5 \) kpc.

Some answers come from direct measurement. Well resolved radio and optical images show significant internal structure, bright knots and filaments, within a jet which initially expands slowly, then collimates at a bright feature which may be a transverse shock. Images taken several years apart reveal temporal variability of bright knots, as well as systematic outwards motion at \( \gamma \sim 3 \).

Some answers come from basic synchrotron theory. The minimum-pressure field \( B \sim 250 \mu \text{G} \) along the jet. The electron DF extends from \( \gamma \sim 2000 \) (radio-loud particles) through \( \gamma \sim 10^6 \) (optical-loud), and probably up to \( \gamma \sim 2 \times 10^7 \) (X-ray loud). If the underlying \( B \) field is not too variable, the synchrotron spectrum reveals the electron DF, which can be approximated as a broken power law over this energy range. We can also derive a reliable lower bound to jet power from this analysis. Referring to (6), \( P_j \gtrsim 4\pi r^2 \gamma^2 \beta \varrho_{\min} c \gtrsim 3 \times 10^{34} \text{erg/s} \), which is larger than the X-ray luminosity from the inner core of the Virgo cluster.30

Further analysis is possible in the context of a physical model. A “double helix” structure is apparent in both optical and radio images of the jet. It can be identified as a combination of helical and elliptical wave modes. If these modes are caused by the Kelvin-Helmholtz (KH) instability and are close to internal resonance (the maximum growth rate), their measured wavelengths and speeds allow determination of the plasma parameters. With such analysis, one can estimate the jet Mach numbers (both internal and external). We estimate the sound speed in the jet plasma to be \( c_s \sim 0.2 - 0.5c \); thus the internal plasma is quite hot but not highly relativistic. It must contain a cooler component in addition to the very energetic particles which make the synchrotron radiation. The external plasma is cooler, \( c_s \sim 0.5c \), and thus at higher density than the jet, but not as cool or dense as the central ICM in Virgo. This suggests that the plasma from the radio jet has partially mixed with the ambient cluster plasma. New X-ray images support this, revealing that the local plasma is disturbed and disordered on this scale.

C Jets in the ICM

When the jet propagates to extragalactic scales, it interacts with the ambient cluster plasma and forms the beautiful structure known as a radio galaxy (RG). We expect this interaction to heat the cluster plasma; eventually the plasma and field carried by the jet should be deposited in the cluster plasma. Just how this will happen depends on how the jet propagates into the ICM and whether it is subject to disruptive instabilities.

1 Propagation and stability

Radio jets are subject to several potentially disruptive instabilities. We know jets propagate at high speeds into the cluster plasma. They will therefore be subject to shear-driven MHD instabilities. Extensive analysis of the KH instability has been applied to jets, including magnetized jets and relativistic jets.33 This work suggests that weakly magnetized jets are most stable when they are supersonic, but that poloidally magnetized jets are most stable when they are subalfvenic. In addition, a jet which is denser than its immediate surroundings tends to be more stable. One might speculate that local changes in the Alfvén mach number, or ambient density, trigger instability in a propagating jet.
In addition, jets may carry a net current. Although this has not received as much attention in the literature, some authors have suggested it\textsuperscript{34}, as do most MHD or ED models of jet formation\textsuperscript{25}. Current-carrying jets are subject to another class of instabilities. While such instabilities have been extensively studied in laboratory plasmas, they have received less attention in laboratory jets. Some interesting recent work\textsuperscript{35} suggests that the kink instability will be the most important for radio jets, but that instead of fully disrupting the jet it may lead to increased internal dissipation and expansion of the jet, followed by recollimation. An interesting further speculation is that the jet may undergo magnetic relaxation, perhaps triggered by an instability, and evolve into a minimum energy state when it reaches large scales\textsuperscript{36}.

2 Three types of sources

Given the range of possible instabilities, one wonders how a jet can manage to propagate at all. This is not yet solved; neither analytic theory or numerical simulation can address the entire issue. Some insight may be gained from a qualitative study of source morphology. Radio galaxies can be divided into three classes, based on their morphology, which have some correlations with radio power and parent galaxy size\textsuperscript{3,37}. These three classes seem to reflect the development of instabilities in the jet.

Jets which remain stable  Consider a jet which is not disrupted by any fluid or current instability (for instance a highly supersonic fluid jet). The rate at which its leading edge propagates into the ICM is governed by momentum conservation. Its advance speed may be supersonic with respect to the ICM, but subsonic with respect to the jet plasma, causing two shock transitions. A bow shock propagates into the ICM, and a quasi-transverse shock stands close to the end of the jet. This latter shock can be a site of strong, local particle acceleration, as well as magnetic field amplification, thus producing the radio bright spot characteristic of many classical-double RGs (Figure 4 shows one example). The jet plasma which has passed through this shock, and decelerated, will expand laterally, forming the “lobes” which characterize this type of RG.

Jets with saturated instabilities  Alternatively, if conditions (such as density contrast or Mach number) are different, instabilities may affect the jet close to its origin. If the jet is subsonic, KH instabilities might lead to the development of turbulence, causing the jet gradually to widen and entrain local cluster plasma. A few RG’s do show the gradual, smooth broadening which this model predicts. In many others, however, the jets show a sudden and dramatic change, starting narrow and well collimated, then quickly flaring out to become a broader, but again stable, flow. Figure 5 shows one example. These “tailed” sources are not yet understood, but it may be that they represent the sudden onset of an instability which saturates without fully disrupting the flow.

Jets which disrupt strongly  A third possibility is that the jet is strongly disrupted close to its origin, and cannot stabilize again. In this case the matter and energy flowing in the jet will be decollimated, impacting the local plasma in a more diffuse flow. One expects the RG to evolve more as a “bubble”, growing with time as en-
ergy enters from the center, possibly with plasma mixing across its outer edge. A few such RG’s are known, all in special environments: they are attached to the central galaxy in a cooling core. We must surmise that something unusual in conditions there leads to this disruption. An example is the jet in M87, which disrupts within a few kpc of the galactic core, creating the halo source shown in Figure 6.

Figure 6  The large-scale halo in M87, in an image from the VLA. The inner jet, shown in Figure 3, disrupts very close to the galactic core. The plasma flow appears to continue in a much less ordered fashion, forming this “bubble” which has partly mixed with the ambient thermal plasma. The image ∼ 80 kpc on a side.

3 Impact on the ICM?

In order to understand how the jet affects the ICM, we need to know its power (equation 6), and also if and where that power is deposited in the ICM. While this last question is currently under active debate, some general comments can be made. Jets which disrupt strongly, and form “bubble” RG’s, must be interacting strongly with the local ICM. We expect the strongest and most localized heating in these cases. Jets which remain stable or quasi-stable out to extragalactic scales may tend to push the ambient plasma aside, but not mix with it strongly (except for shear-surface or mixing instabilities along the lobes or tails). We might expect weaker local heating of the ambient plasma in these cases, although the jet and cluster plasmas must eventually mix. The energy deposition may simply occur on larger scales for these types of RG’s.

V Issues and Controversies

Although we have known about the radio jets and the cluster plasma for about 30 years (since they were detected with radio interferometers and X-ray satellites, respectively), the physical picture is still unclear. I present a few problems currently under discussion.

A Transport Physics

It is not clear whether collisional transport can be applied to all problems in the cluster environment.

In the context of cooling flows, many authors have noted that heat transport at the rate allowed by Spitzer conductivity would stop the putative strong cooling and inflow. Many cooling flow models simply ignored thermal conduction. Some authors suggested that magnetic fields could lower the conduction orders of magnitude below the Spitzer value (as needed to preserve the early models). Other authors modelled heat transport assuming various descriptions of a disordered magnetic field. No clear consensus has emerged but most workers find a tangled field will lead to only a modest suppression of heat flow relative to the Spitzer value.\(^{39}\) There has also been some work on suppression of heat flow by plasma instabilities, again without a clear consensus.\(^{40}\)

Changing views on cooling cores, in particular the inability to find the large reservoir of cooled gas, may make this problem seem less critical. However, the new detection of cold fronts again raises the issue. These fronts are thinner than the Coulomb mean free path, which is ∼ 10 kpc in the cluster plasma. They must be protected from heat transport at the Spitzer level; indeed, they must be collisionless discontinuities. They have been modelled in terms of strongly sheared magnetic fields, parallel to the cold front\(^{15}\); I am not aware of any modelling addressing whether plasma turbulence might support such a thin front.

B Magnetic Field Maintenance

There are many questions yet to answer here. We do not even know the structure of the cluster magnetic field. Is it strongly filamented? Is it enhanced local to embedded radio galaxies? Have we correctly identified its order scale at the small, ∼ 10 kpc value from the Faraday observations? Or is it not a coincidence, that this scale is similar to the Coulomb mean free path?

We must also ask about the origin and maintenance of the field. Some authors envision the field as primordial, enhanced by the collapse of the cluster. However, if the order scale of the field is ∼ 10 kpc, the turbulent dissipation time will be short compared to the cluster life. One possibility is that turbulence or flows in the cluster
support the field. Turbulence can take a small seed field (say from early-epoch galaxy ejecta) and, given enough time, enhance it to reach approximate equipartition with the kinetic energy of the flow. An alternative view is that the field and flux have been injected from active galaxies. The second picture may have trouble explaining how the magnetized jet plasma can mix effectively with the cluster plasma to maintain fields throughout the cluster. The first picture is appealing to me, but our lack of understanding of turbulence in the ICM has made it hard to test quantitatively.

C Particle acceleration

From cosmic rays to clusters of galaxies, this is an important topic in plasma astrophysics. How does the plasma maintain a significant, nonthermal population of highly relativistic particles, against radiative losses and thermalizing collisions? There must exist a mechanism which preferentially energizes particles already at high energies; otherwise we would simply see plasma heating.

There are several “usual culprits”. Shock acceleration can occur via Fermi acceleration, that is multiple scatterings, across the shock face, in quasi-parallel shocks; or along the shock face, using the induced potential drop, in quasi-perpendicular shocks. Plasma turbulent acceleration has been proposed in many forms. This is a stochastic process, in which fluctuating electric fields in plasma waves slowly energize the particles. For relativistic particles, the cyclotron resonance with Alfven waves is usually proposed; but transit time damping in strong turbulence has also been suggested. Electrodynamic acceleration is possible if an ordered electric field exists, such as in current sheets or double layers. Reconnection acceleration is a variant of this last.

Acceleration in radio galaxies has been an ongoing question. Both shock and turbulent acceleration have been suggested. Some of the issue is determining from the dynamics what acceleration sites can exist away from the black hole. Shocks can be identified in the outer hot spots in classical double RG’s (as in Figure 4); some authors suggest the bright knots in jets (as in Figure 3) are also shocks. However, there is not always evidence for an ordered shock at acceleration sites. Other authors propose turbulent acceleration, possibly related to the outer shear layer of the jet.

The case is less clear for the cluster plasma, because it is not yet established whether nonthermal plasma is common or rare. Several authors (like myself) believe it will turn out to be common, in which case in situ acceleration is also needed in the cluster. Once again both shock acceleration and turbulent acceleration have been invoked. Probably both are occurring. Large, ordered shocks are expected in major mergers, while smaller shocks as well as turbulence are expected more generally in smaller mergers. Because smaller mergers seem to be so common, and particle acceleration a direct consequence, it seems likely that the ICM in most clusters must contain a relativistic component.

D Energy Sources for the ICM

Our picture of clusters has changed. Early work in the field assumed that clusters were static, self-contained entities in which nothing much had happened since their creation. We now know that they are dynamic and still evolving. In particular, the cluster plasma is being energized from within and without. We can identify three drivers operating today; the challenge is to quantify them.

The first comes from normal galaxies within the cluster. As they move through the cluster plasma, they drive turbulence and possibly bow shocks in that plasma. This must be operating in every cluster. Because galaxy counting and galaxy masses are well understood, this effect can be estimated quantitatively; it turns out to be only of modest importance.

A second driver is active galaxies in the cluster. As discussed above, the mass and energy driven out in their jets must eventually be deposited in the ICM. These galaxies are rare, only about one per rich cluster, with some tendency to be located in the core. In addition to the jet power, we must determine the duty cycle of an AGN. Models of radio galaxies suggest they are short-lived compared to the cluster; it may be that the galactic core is “active” only part of the time. These problems are not yet well understood.

Finally, the ICM must be energized at present by the motions of clumps of dark matter which continue to merge with the cluster. General cosmological studies, which constrain how often clumps merge and the energy per clump, suggest plenty of energy is available to the ICM at the present time. However, we do not yet understand the details. Numerical simulations are the best tool here; but they are only beginning to address important details such as the small-scale motions of the dark matter and the efficiency with which it couples to the cluster plasma.

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references


2. In this and all equations in this section, I suppress physical constants, to highlight the dependence on important parameters such as \( \nu, B, T, n \).


22. G. Giovannini and L. Feretti, New Astronomy, 5, 535 (2002); in addition a systematic VLA search of a complete sample is being carried out by F. Owen, T. Markovic, and myself.


26. Jet deceleration will partially offset these losses, but this can be shown quantitatively not to solve the entire problem.


