Magnetic reconnection in large-scale cosmic plasmas

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X-ray emitting hot plasmas of a temperature 2–12 keV, associated with galaxy clusters, constitute the most dominant form of baryons in the universe. The plasma is thought to be magnetized at least to 0.1–1 nT, although the β value is relatively high at 10–100. The plasma is confined by gravity of each cluster in a stable manner, but the member galaxies are moving through it with an approximately transonic speed. Therefore, the plasma must be in a magnetohydrodynamically turbulent condition, where frequent magnetic reconnection is expected to take place. Mainly based on observations with the *ASCA* X-ray Observatory, evidence for such magnetic reconnection is accumulating.

1. Introduction

The matter in the universe is found mostly in the form of plasmas. Accordingly, the plasma-physics aspects have been developed extensively in planetary and inter-planetary disciplines, as well as solar coronal studies. Nevertheless, attempts to describe larger astronomical systems in the light of plasma physics have been surprisingly scarce. This is probably because various plasma effects (e.g., detailed configuration of magnetic fields) are difficult to detect via astronomical remote-sensing techniques. In fact, the nature of the magnetic solar corona had not been fully recognized until fine-resolution X-ray images of solar coronae became available with *Skylab*, *Yohkoh*, and *SOHO*.

This paper presents a novel attempt to describe the largest astronomical objects, clusters of galaxies, under a full magnetohydrodynamic (MHD) viewpoint. Filled with hot tenuous plasmas, these objects are thought to provide an ideal and fascinating laboratory to study magnetoplasma effects.

2. Clusters of Galaxies

A galaxy is a system formed by $\sim 10^{11}$ stars, each like the sun, and some amount of diffuse matter. The stars are held together by gravity, which is produced not only by the stars themselves but also by dark matter (DM), of which the nature is still unclear. The DM presumably forms a large halo surrounding the optically visible galaxy.

Hundreds of galaxies can also be bound together by gravity, to form an astronomical system of a higher hierarchy, called a cluster of galaxies (or a galaxy cluster). There are more than 10^4 catalogued clusters in the sky. A galaxy cluster is primarily identified in the visible light as a grouping of galaxies over a narrow spatial volume, so that its primary constituent is naturally thought to be stellar component. In reality, however, there are two more dominant components of galaxy clusters.

One is tenuous hot plasma, called intracluster medium (ICM), compressed and confined by gravity. It permeates the cluster volume and emits bright diffuse X-rays, including thermal Bremsstrahlung continua and emission lines from heavy ions. Figure 1 gives a comparison of the optical and X-ray images of a cluster. Surprisingly, the spatially-integrated mass of the ICM is comparable to, or often a few times higher than, that of the stars integrated over all member galaxies. Therefore, the ICM provides the most dominant known form of baryons in the universe.

The other is again the DM, which actually dominates the total mass in each cluster. Its presence can be inferred because the total gravitating mass M_G necessary to bound the hot plasma much exceeds the estimated baryonic mass (sum of the stellar and the plasma components). Specifically, by assuming the thermal ICM pressure to balance the gravity, we can estimate M_G within a 3-dimensional radius R as (Sarazin, 1988)

$$M_G(R) = -\frac{kTR}{\mu G m_p} \left(\frac{\mathrm{d} \ln p}{\mathrm{d} \ln R} \right), \qquad (1)$$

where G is the constant of gravity, k is the Boltzmann constant, T is the ICM temperature, $\mu \sim 0.6$ is the mean particle mass in unit of the proton mass m_p, and p is the ICM pressure. When integrated up to $R \sim 1$ Mpc ($= 3.08 \times 10^{22}$ m), a typical cluster has $M_G(R) = 10^{14 \sim 15} M_\odot$, of which $\sim 90\%$ is carried by the DM, $\sim 7\%$ by the ICM, and only $\sim 3\%$ by the stellar component.

3. Properties of the ICM
3.1 Basic parameters of the ICM

The ICM has a typical temperature of 2–12 keV, presumably heated by adiabatic compression when the cluster formed. The ICM consists mainly of primordial gas (76% hydrogen and 23% helium by weight), plus heavier elements (O, Si, Fe etc.) to a level of 0.25–0.3 solar abundances. Therefore, the ICM contains matter once processed in the stellar interior, and then ejected, by supernovae and other mechanisms.
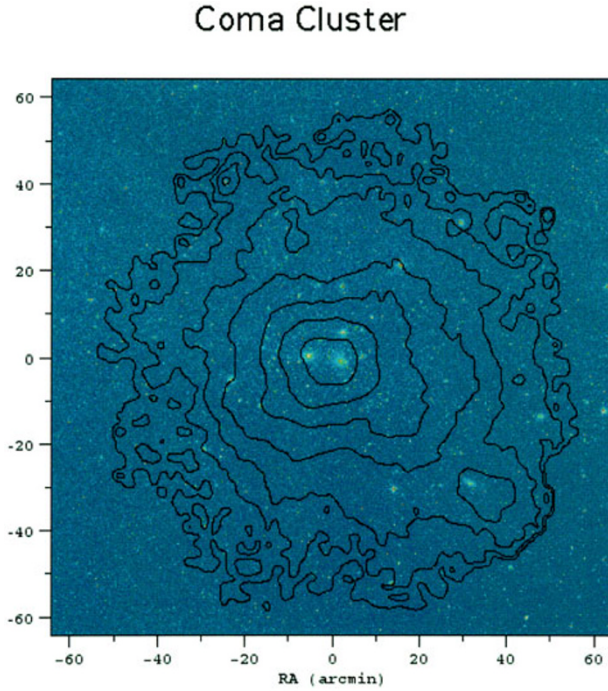
Coma Cluster

Fig. 1. X-ray surface brightness contours of the Coma cluster of galaxies, superposed on an optical image.
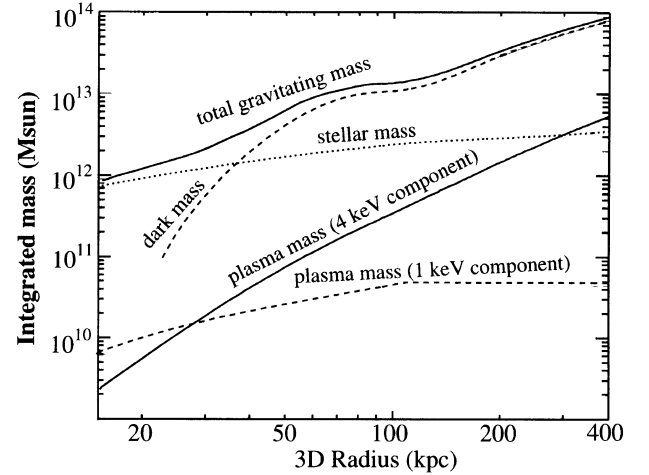

Fig. 2. Radially integrated profiles of various mass components of the Centaurus cluster (Ikebe *et al.*, 1999); the total mass (upper solid curve), the stellar mass (dotted curve), the hot ICM mass (lower solid curve), and the cool plasma mass (lower dashed curve). The upper dashed curve represents the DM mass, obtained by subtracting the three baryonic components from the total mass.

The radial profile of the ICM density is approximated by a Lorenzian-like form as

$$n(R) = n_0 \left\{ 1 + (R/a)^2 \right\}^{-3\gamma/2}, \qquad (2)$$

where $n_0 = 10^{3\sim 4}$ m^{-3} is the central density, $a = 100 \sim 250$ kpc is a characteristic core radius, and γ is an empirical shape parameter which usually takes values of $\sim 2/3$. An example of the integrated mass profile of the ICM is given in Fig. 2, together with the total mass profile of Eq. (1) and the stellar mass profile. In this particular case, the integrated ICM mass overwhelms the stellar mass beyond $R \sim 300$ kpc.

Because of the high temperature and low density, the ICM can be considered as the most ideal, collision-less, fully-ionized, classical plasma. Actually, the ratios among the inter-particle separation, the Debye length, the ion Larmor radius (for a magnetic field of 0.1 nT), the mean free path due to classical Coulomb scattering, and the system size (~ 1 Mpc), become approximately $1 : 10^3 : 10^{9.5} : 10^{19} : 10^{22.5}$.

3.2   The ICM magnetization

Like most of the other astrophysical plasmas, the ICM is generally magnetized (Kronberg, 1994). According to measurements of the Faraday rotation of active galaxies in clusters and background quasars, the magnetic field averaged along the line of sight is typically $\langle B \rangle = 0.1 \sim 1$ nT (Ge and Owen, 1994). Diffuse synchrotron radio emission observed from a limited number of clusters gives an additional support to the ICM magnetization.

The nominal equipartition field strength in the cluster central regions is ~ 3 nT, so that the measured $\langle B \rangle$ implies a considerably high-β ($10 \sim 100$) situation. However, the field lines may be extremely tangled, in which case $\langle B \rangle$ significantly underestimates the local field strength. We presume the local field strength could be as strong as the equipartition value. In any case, the magnetic Reynolds number is absurdly high.

3.3   Dynamical and thermal state of the ICM

Since the ICM is hydrostatically confined by gravity in a spherical potential, we expect it to be in the condition of minimum free energy, and hence to suffer from none of major MHD instabilities (interchange-type ones, current-driven ones, etc.). Since the radiative cooling time of the ICM

$$t_c = 2 \times 10^9 \left(\frac{T}{4 \text{ keV}} \right)^{-1/2} \left(\frac{n}{10^4 \text{ m}^{-3}} \right)^{-1} \text{ yr} \qquad (3)$$

is typically $\sim 1/6$ of the Hubble time, the ICM near the cluster center would gradually lose energy via X-ray radiation, causing a slow radial in-flow of the ICM to compensate the radiative energy loss. This idea, called cooling flow, has been developed as a popular account of X-ray properties of clusters (Fabian, 1994).

The cooling-flow hypothesis, however, ignores an important fact: a large number of member galaxies are actually moving through the ICM, with a velocity of $300 \sim 1000$ km s^{-1} which is close to the ICM sound speed. (That is, in each cluster, the galaxies and the ICM have comparable energies per unit mass.) Astrophysicists would think that the galaxies swim through the ICM without much interaction, since the galaxy motion is at most transonic. However, plasma physicists would think otherwise, since the galaxies, having their own inter-stellar plasmas and inter-stellar magnetic fields, must be "opaque" to the ICM in the MHD sense. Therefore, the galaxy motion is expected to strongly "drag" the ICM, causing intense MHD turbulence where frequent magnetic reconnection should occur. Possible "wake" from such an interaction has recently been detected in X-rays by Drake *et al.* (2000). As a result, kinetic energy of the galaxies will be dissipated efficiently into the ICM heating and particle acceleration. More detailed aspects of such processes are described in Section 4.

4. Evidence for Galaxy-ICM Interaction

Based mainly on X-ray observations of clusters of galaxies using *ASCA* launched in 1993 (Tanaka *et al.*, 1994), we have obtained a number of new results which can be understood as a consequence of MHD interactions between the moving galaxies and the ICM (Makishima, 1996, 1997a,b, 1999a,b).

4.1 Two-phase picture of the ICM

Although the ICM is relatively isothermal in outer cluster regions, its temperature has long been known to decrease markedly toward the center of many clusters. This was so far interpreted as a result of ongoing ICM cooling (i.e., the cooling flow), because of the short cooling time of Eq. (3).

With *ASCA*, we have confirmed the presence of cool (~ 1 keV) emission components within ~ 100 kpc of the center in many clusters of galaxies (e.g. Fabian *et al.*, 1994). However, what we have actually observed is somewhat different from the prediction of the cooling-flow hypothesis. The plasma has been found to consist mainly of two (hot and cool) components (Fukazawa *et al.*, 1994) as exemplified in Fig. 3, rather than displaying a continuous temperature distribution characteristic of ongoing cooling. The central volume appears to be occupied predominantly by the hot component, where the cool component is somehow mixed in (Fukazawa *et al.* 1994; Ikebe *et al.*, 1997, 1999), forming a "two-phase" region. The cool component is clearly associated with the "cD" galaxy (Fukazawa *et al.*, 2000), the dominant elliptical galaxy found at the center of about two-thirds of clus-
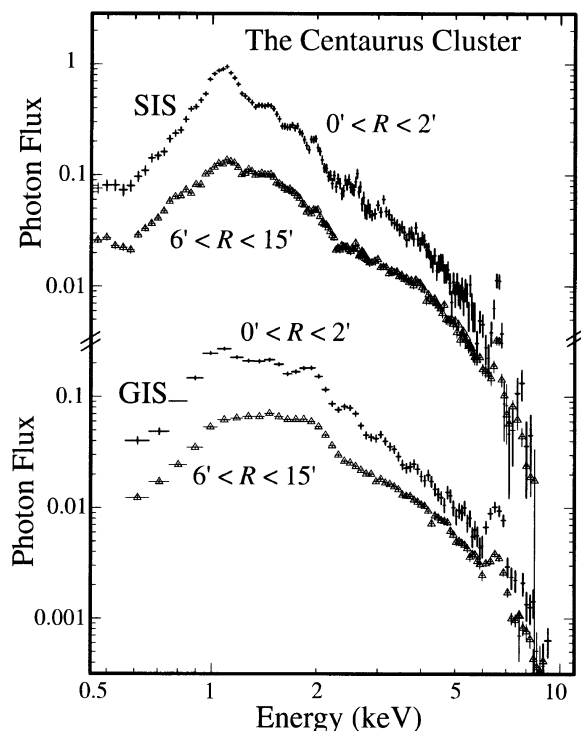

Fig. 3. The X-ray spectra of the Centaurus cluster (Fukazawa *et al.*, 2000) obtained with the two instruments (SIS and GIS) onboard *ASCA*. Triangles represent the spectra taken from the outer cluster region, where an isothermal (~ 4 keV) ICM produces Fe-K emission line at 6.6 keV. Crosses show the spectra from the central 100 kpc region, where an additional cool (~ 1 keV) component gives rise to S-K (at ~ 2.5 keV), Si-K (at ~ 1.9 keV), and Mg-K (at ~ 1.4 keV) lines, as well as the strong Fe-L complex over the 0.7–1.2 keV region.

ters; clusters without a cD galaxy lack the cool component (Tamura *et al.*, 2000). The central two-phase region exhibits a considerably higher metallicity and a slightly higher Fe/Si ratio than the bulk of the ICM, suggesting a significant influence from Type I supernovae in the cD galaxy (Fukazawa *et al.*, 2000). Furthermore, we have discovered a central "dimple" in the gravitational potential around each cD galaxy (Xu *et al.*, 1998), which is suspected to have caused overestimates of the cooling-flow rate.

Although we have thus arrived at a steady-state two-phase picture instead of the cooling-flow scenario, we must explain how the two phases are thermally insulated from each other, and what prevents the cool phase from the radiative collapse. For this purpose, we assume that the MHD turbulence produces chaotic magnetic fields all over the cluster volume, except at the very center where the cD galaxy is standstill with respect to the ICM. Then, a well-ordered magnetic corona will develop around each cD galaxy, with many closed magnetic loops anchored to it. We assume the loop interior to be filled with the cool phase originating from the cD galaxy, whereas the exterior is permeated by the hot ICM (Makishima, 1997a,b, 1999a,b). Thus, the two phases can be thermally decoupled.

4.2 ICM heating by the galaxy motion

In order for the cool phase to be sustained for nearly the Hubble time, it must be heated by some mechanisms, against its radiative energy loss with a typical luminosity of $10^{35.5\sim36.5}$ W. We speculate that the motion of other galaxies around the cD galaxy will generate intense MHD turbulence around the central corona, wherein frequent magnetic reconnection heats the ICM.

Then, is the proposed mechanism efficient enough? For a typical cluster containing ~ 100 galaxies with a velocity dispersion of $v = 700$ km s^{-1}, the ICM heating luminosity due to the galaxy drag becomes $L_{\text{drag}} \sim 100\xi n m_{\text{p}} v^3 S \sim 2 \times 10^{38}\xi$ W (Makishima, 1999a,b). Here ξ is the efficiency of thermalization, $n \sim 3 \times 10^3$ m^{-3} is the ICM density, and $S = \pi r^2$ with $r \sim 20$ kpc is the MHD cross section of each galaxy. Even if ξ is moderately low, e.g. ~ 0.05, we expect $L_{\text{drag}} \sim 1 \times 10^{37}$ W. Further assuming a total stellar mass of 1×10^{13} $M_\odot$, the total kinetic energy in galaxies, 5×10^{54} J, can sustain the heating for $\sim 1.6 \times 10^{10}$ yr, i.e. over the Hubble time.

Invoking a loop-like geometry has another merit, that the heating and cooling can be balanced in a stable manner, via a mechanism analogous to the Rosner-Tucker-Vaiana (1978) self-regulating mechanism which is operating in the solar corona (Kano and Tsuneta, 1995). That is, if the heating rate due to reconnection becomes too low, the loops become thinner, compressed by the external pressure, and the conductive flux automatically reduces to recover the thermal balance.

4.3 Reaction to the galaxies

If the ICM is actually exerting friction to the moving galaxies, we should expect them to receive significant reactions from the ICM. In fact, we find several pieces of evidence supporting this idea.

As is clear from Fig. 2, the galaxy distribution is generally more concentrated than the ICM mass profile; within ~ 100 kpc, the ICM mass is only $\sim 10\%$ of the stellar mass. Although we cannot rule out the possibility that the efficiency

of galaxy formation was lower in outer cluster regions, it may be explained alternatively as a manifestation of gradual galaxy infall to the potential bottom, as a consequence of the ICM friction. In other words, the galaxies are inferred to have lost their kinetic energies, which in turn were deposited onto the ICM to make it more extended.

The proposed interaction with the ICM will also accelerate mergers between a pair of close-by galaxies, because their orbital angular momentum can be dumped on the ICM by launching helical Alfvén waves. We hence expect a dense ICM environment to enhance the mergers of spiral galaxies into bigger and fewer elliptical galaxies. Actually, it is well known that the fraction of spiral galaxies rapidly decreases to the cluster center (e.g. Whitmore and Gilmore, 1993). Ramirez and de Souza (1998) report that orbits of elliptical galaxies in clusters tend to be radial, while those of spirals are rather circular so that they avoid the central region during their journey. Furthermore, as to galaxy groups (which are the poorest of clusters of galaxies), X-ray luminous (i.e. plasma-rich) systems have been found to contain a higher fraction of elliptical galaxies (Mulchaey et al., 1996). All these facts support our conjecture.

Another important fact from the evolutionary viewpoint is that distant clusters contain a large number of small, disturbed, blue spiral galaxies, while nearby ones do not (Dressler et al., 1994). We can interpret this finding that the spiral galaxies in the past have merged into ellipticals, through the enhanced galaxy-galaxy interaction aided by the ICM. This mechanism can be much more efficient than the simple gravitational close encounter proposed by Moore et al. (1996).

4.4 Particle acceleration

Yet another possible consequence of the proposed galaxy vs. ICM interaction is particle acceleration by the magnetic reconnection. In the vast intracluster space, the particles are expected to attain very high energies because of rather low energy loss rate there. Actually, according to an empirical scaling law proposed by Makishima (1999b), the maximum particle energy attainable in an acceleration site is roughly given by $E_{max} = v \times B \times L$, where v is the typical internal velocity of the system, B is again the magnetic field, and L is the system size. Substituting $v = 7 \times 10^5$ m s^{-1}, $B = 1$ nT, and $L = 1$ Mpc, we obtain $E_{max} \sim 10^{19}$ eV, which is close to the energy of the highest-energy cosmic rays (Takeda et al., 1998).

The reduced energy-loss rate, on the other hand, implies a difficulty of detecting such energetic particles. However, there are increasing number of detections of non-thermal radiation from clusters and groups of galaxies, which signals the presence of energetic particles. One is the excess hard X-rays detected with *BeppoSAX* from several clusters (Fusco-Femiano et al., 1999; Kaastra et al., 1999), which may be inverse-Compton photons or non-thermal Bremsstrahlung radiation (Sarazin and Kempner, 2000). Another is excess soft X-ray signal detected with *EUVE* from several clusters (e.g., Sarazin and Lieu, 1998), interpreted as an inverse-Comptonization of the cosmic microwave photons, although thermal interpretation is still possible (Lieu et al., 1999). The other is clear hard X-ray tail, observed with *ASCA* (Fukazawa et al., 2001) from a fair number of galaxy groups, which is interpreted as either the inverse-Compton radiation by extremely relativistic particles or non-thermal Bremsstrahlung by semi-relativistic electrons.

5. Future Prospect

In order to strengthen the plasma-physics view of galaxy clusters developed in the present work, a number of future observations in X-rays and γ-rays can be proposed. One is the high-resolution spectroscopy of the ICM X-rays, where we expect to find broadening of the atomic emission lines to a level of several hundred km s^{-1}, due to the predicted plasma turbulence. Another is higher-sensitivity search for non-thermal radiation from galaxy clusters and groups, to obtain further insight into the possible particle acceleration. These two observations could have been carried out best with the X-ray Spectrometer (XRS) and the Hard X-ray Detector (HXD; Takahashi et al., 1996) respectively, both onboard the 5th Japanese cosmic X-ray satellite ASTRO-E developed under an extensive Japan-US collaboration. However, to our great regret, ASTRO-E has been lost on 2000 February 10, because of a malfunctioning in the first stage of the M-V-4 launch vehicle. We are currently practicing our best effort to rebuild ASTRO-E together with its onboard instruments, and to launch it on the soonest possible occasion.

Even though ASTRO-E has been lost, we can utilize the other two high-performance X-ray observatories, the American *Chandra* and the European *XMM-Newton*. Using *Chandra* with the unprecedented angular resolution, we may search the ICM surface brightness around cD galaxies for the proposed filamentary structure. We may also utilize *XMM-Newton* to accurately measure the ICM profiles of distant clusters, and compare the results with the optical galaxy density profiles. If our conjecture on the galaxy infall is correct, we may find an evolutionary effect in the radial galaxy distribution with respect to the X-ray extent.

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