STATISTICS OF RADIO-X-RAY EMISSION AND MAGNETIC FIELDS IN THE INTERGALACTIC MEDIUM

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X-ray observations have demonstrated that the intergalactic medium in many clusters (cf. Coma, Perseus) contains a thin, hot plasma that may be produced by the accretion process in the gravitational potential of clusters with radiative cooling; this is usually called "cooling flows" (Fabian, Nulsen, and Canizares 1984; Sarazin 1986). On the other hand, the existence of radio halos in some clusters has been reported (Coma: Jaffe, Perola, and Valentijn 1976; A401: Roland et al. 1981). In addition, many elliptical galaxies in the center of clusters are also strong synchrotron radio sources. These radio emissions provide evidence for large amounts of relativistic electrons associated with the active phenomena in or around these galaxies and clusters. We can estimate the values or limits on the magnetic field in the cluster from the limits on the inverse Compton X-ray emission with the synchrotron radio emission (cf. Jaffe 1980). The intracluster field strength B_o is roughly 1 μG. It has been suggested that the influence of cosmic rays and magnetic fields is important for the properties and dynamics of the intercluster medium (Böhringer and Morfill 1988; Soker and Sarazin 1989). If cooling flows are real, this inward flow can impede the escape of the cosmic rays from the central galaxies in clusters and enhance the magnetic field. The confinement of the cosmic rays and the magnetic field in the center of clusters affects the gas of the intracluster medium.

If we assume that the inward flow is spherical, symmetric, and in steady state, and the magnetic field is approximately frozen-in to the plasma in cooling flows, the magnetic field can be compressed or enhanced, relative to the increasing density and the dynamo effects. It varies as

$$P_B \approx P_{BO}\,(r/r_o)^{-4}, \tag{1}$$

where we assume $r_o \approx 100$ kpc as the cooling radius. First, we will consider the effect of magnetic fields associated with the accreting plasma medium. From the X-ray observation by Stewart et al. (1984), the electron density is well fitted by

$$n_e(r) = 1.5 \times 10^{-2}\,\frac{(r/30\ \mathrm{kpc})^{-0.8}}{1 + (r/30\ \mathrm{kpc})}\ \mathrm{cm}^{-3}. \tag{2}$$

Since the temperature seems to change little, we assume $T \approx 5 \times 10^7$ K in this flow and then the thermal pressure can be estimated. Thus, the pressure of the magnetic field becomes comparable to the thermal pressure at $r_B \approx 26(B_o/1\ \mu\mathrm{G})^{2.9}\,(T/5 \times 10^{-7}\ \mathrm{K})^{-5.8}$ kpc. In this estimate, the magnetic pressure dominates the thermal pressure inside this radius. However, these highly compressed and enhanced magnetic fields are suppressed by the reconnection effect. In this region, the first (Petscheck) reconnection is especially important for the flow dynamics. This driven reconnection produces the magnetic neutral sheet and X-shaped, slow shock waves in which the magnetic field lines are strongly bent, and the magnetic stress in this region can produce the high-velocity plasma flow along the neutral line. The terminal velocity becomes the Alfvén velocity at the prereconnected region. If we assume that the magnetic energy is in

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S. Bowyer and C. Leinert (eds.), The Galactic and Extragalactic Background Radiation, 414–415.

equipartition with the thermal pressure, the rate of energy released by the reconnection inside r_B, which is comparable to the accretion rate of thermal energy $P\dot{M}_{r=r_B}/\rho$ for cooling flow, can be written as:

$$L_{\rm rec} \approx 5 \times 10^{43} \left[\frac{T}{5 \times 10^7\ {\rm K}}\right] \left[\frac{\dot{M}}{10^2\, M_\odot}\right] {\rm erg\ s^{-1}}. \qquad (3)$$

In this process, the magnetic energy is released to the kinetic and internal energy of the plasma and the energy of nonthermal particles. The turbulent and small-scale motion into the flow can be induced. Böhringer and Morfill (1988) have argued that the cosmic rays are generated in the central galaxies and have diffused out, and that they may induce the convective motion and the turbulence. However, magnetic reconnection can induce the turbulence in a more extended region ($\approx r_B$).

Various models for particle acceleration have been proposed. These can be divided into the direct electromagnetic acceleration model like some pulsar models, the shock drift model of Decker and Vlahos (1986), and the statistical acceleration model. The latter consists of acceleration in a diffusive shock (Blandford and Ostriker 1978) and second-order Fermi acceleration in turbulence of MHD waves (Ramaty 1979). In the intracluster medium inside the equipartition radius r_B, the most likely mechanism of particle acceleration seems to be strong MHD turbulence, which may be induced by magnetic reconnection as discussed above. In this model, we can obtain the energy spectrum,

$$\frac{dJ}{dE} \propto \beta K_2 \left[2 \left[\frac{3\beta}{\alpha T}\right]^{1/2}\right], \qquad (4)$$

where $\beta = v_p/c$, K_2 is the second modified Bessel function, T is the time scale of the energy loss, and α is the rate of the acceleration, which is defined as $3v_A^2/2Lc$. If the acceleration time scale is shorter than the energy loss time, approximately $\alpha T << 1$, $dJ/dE \propto E^{-3}$. Then, the synchrotron radio emission luminosity becomes proportional to $\nu^{-3/2}$. This power-law index -3/2 is similar to the observed value of the index -1.2 for Coma (Jaffe 1977). This suggests that the generation of cosmic rays in diffuse radio cluster sources like the Coma Cluster may be related to the magnetohydrodynamical properties of the intercluster medium. In this picture, for the clusters associated with diffuse radio halos and X-ray halos, even if the magnetic field is not so disordered in the outer part of the cluster, the magnetic field in the center is turbulent. These properties can be observed from Farady rotation.

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