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Physics of the Largest-Scale Hot Plasmas in the Universe

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The overall energy-density budget of the Universe is dominated (~73%) by "Dark Energy", and yet about 23% is attributed to "Dark Matter (DM)". However, our knowledge of the Universe, including that of these two enigmatic components, is provided mostly by baryons (i.e., ordinary matter composed of ions), which carry only the remaining 4%.

When the Universe was born 13.8 billion years ago, DM and baryons were distributed both almost uniformly, but soon fluctuations started to develop in the DM distribution, due to its gravitational self-attraction. Then, by the DM gravity, baryons were adiabatically compressed to become very hot. A minor fraction of these hot baryons became so dense as to cool by radiation and collapse into celestial bodies, which we observed today as a hierarchy of stars→galaxies→clusters of galaxies.

A cluster of galaxies is a gigantic structure, regarded primarily as a DM clump. Optically, it is observed as an assembly of hundreds of galaxies. In X-rays, in contrast, each cluster is observed as a bright extended source, because the remaining major portion of baryons, which survived the cooling collapse, are confined by gravity to individual clusters, and emit Bremsstrahlung X-rays. These plasmas, called ICM (Intra-Cluster Medium), are hot with a temperature of $T \sim 10^8$ K, tenuous with a density of $n \sim 10^{-3}\,\mathrm{cm}^{-3}$, and magnetized to a few μG (or $\beta \sim 100$). Since the ICM is thus the most dominant form of known cosmic baryons, plasma-physical understandings of its property, evolution, and dynamics will provide clues to puzzles and mysteries of the Universe.

As clear from Fig.1, the ICM is by far the most ideal classical plasma with weak magnetization. In addition, due to its hydrostatic confinement by gravity (a condition never achieved in laboratory), the ICM is nearly free from various instabilities. Nevertheless, in each cluster, a large number of galaxies are moving through the ICM with transonic velocities. Interactions between the ICM and these galaxies are expected to drive series of plasma-physical phenomena, as explained below.

The first aspect of the ICM-galaxy interaction is heating of the ICM by the moving galaxies. In the 1980's, the ICM in all clusters of galaxies were thought to lose its thermal energy on cosmological time scales into the X-ray radiation, so that the ICM pressure in cluster centers decreases. This was thought to generate an inward plasma flow, which further accelerates the radiative cooling. The concept of this thermal instability, called "cooling flows", once prevailed X-ray studies of galaxy clusters, but our observations with the *ASCA* observatory found cooling flows nowhere [1]. Therefore, the ICM must be somehow heated against the radiation, with a luminosity which is an order of magnitude higher than is available from supernovae. We consider that the energy transfer from the moving galaxies to the ICM provides the most natural heating source of the ICM [1].

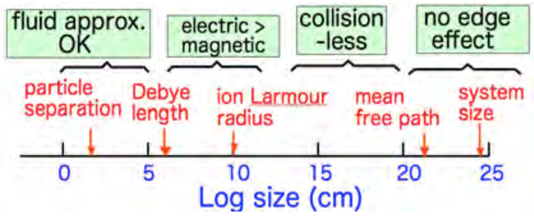

Fig.1. Typical plasma-physical length scales of the ICM.

The 2^{nd} aspect of the problem is reaction from the ICM to the moving galaxies. By observing two samples of clusters, covering from our vicinity to a redshift of ~1 (i.e., when the Universe was ~0.4 times as old as today), we have observationally demonstrate that the galaxies have been gradually falling to the centers of their host clusters [2,3]. This is most likely due to drag force which the galaxies receive from the stationary ICM. Although the idea is very natural from a viewpoint of plasma physics, surprisingly this phenomenon has never been predicted or noticed by any astrophysicist before.

In each cluster, galaxies in peripheral regions tend to show spiral morphology, whereas those at central regions are mostly elliptical ones. In addition, distant (younger) clusters host larger fractions of spiral galaxies than nearby (older) ones. These "environmental effects" have been well known via observations, but no adequate explanation has so far been given to them. In our view, the perturbations from the ICM on the galaxies must be the prime driving force of their metamorphosis from spirals to ellipticals. This would solve one of the major puzzles with the cosmological evolution of galaxies.

Finally, through studies of cosmic particle acceleration sites, we arrived at a scaling law shown in Fig. 2: the maximum electron energy observed in various objects scales well with the triplet vBL, where v, B, and L are the typical velocity, magnetic field, and size of the system, respectively [4]. It suggests that electric fields induced by plasma motions play an important role in particle acceleration. Since galaxy clusters are expected to have $vBL \sim 10^{18}$ V, they are candidate for the yet unknown production site of the highest-energy cosmic rays.

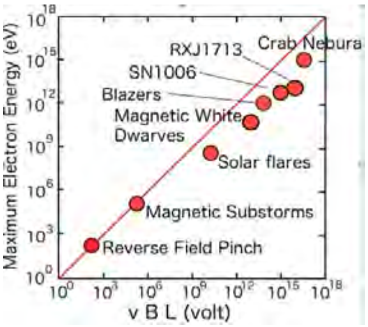

Fig.2. A scaling for cosmic particle acceleration [4].

References

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