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The X-ray Fundamental Plane of Clusters of Galaxies

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Abstract. We analyze the relations among the central gas density, core radius, and temperature of X-ray clusters by plotting the observational data in the three-dimensional ($\log \rho_{\rm gas,0}$, $\log r_{\rm c}$, and $\log T_{\rm gas}$) space and find that the data lie on a 'fundamental plane'. We discuss the implications of the plane.

1. Introduction

Correlations among physical quantities of clusters of galaxies are very useful tools for studying formation of clusters and cosmological parameters. In particular, the luminosity ($L_{\rm X}$)- gas temperature ($T_{\rm gas}$) relation in X-ray clusters has been studied by many authors. Observations show that clusters of galaxies exhibit a correlation of approximately $L_{\rm X} \propto T_{\rm gas}^3$. On the other hand, a simple theoretical model predicts $L_{\rm X} \propto T_{\rm gas}^2$. This discrepancy remains one of the most important problems in clusters of galaxies. In this paper, we reanalyze the observational data of X-ray clusters and study the relations in detail based on the idea of fundamental plane.

2. Data

We use the observational data of the central gas density, $\rho_{\rm gas,0}$, core radius, $r_{\rm c}$, and gas temperature, $T_{\rm gas}$, of 45 clusters in the catalogues of Mohr, Mathiesen, & Evrard (1999) and Peres et al. (1998). The data plotted in the $(\log \rho_{\rm gas,0}, \log r_{\rm c}, \log T_{\rm gas})$ space are fitted with a plane,

$$\rho_{\rm gas,0} \propto r_{\rm c}^{-1.39} T_{\rm gas}^{1.29} . \tag{1}$$

We call the plane the fundamental plane.

Moreover, the data on the plane form a band

$$\rho_{\rm gas,0} \propto r_{\rm c}^{-1.3\pm0.2} , \tag{2}$$

$$T_{\rm gas} \propto r_{\rm c}^{0.06\pm0.1} \propto \rho_{\rm gas,0}^{-0.05\pm0.1} . \tag{3}$$

We refer to the band as the fundamental band. Relation (3) indicates that the major axis of the fundamental band is nearly parallel to the $\log \rho_{\rm gas,0} - \log r_{\rm c}$ plane, i.e., temperature varies very little along the fundamental band. Thus, the observed relation $L_{\rm X} \propto T_{\rm gas}^3$ should be the correlation along the minor axis of the band on the fundamental plane as is explicitly shown by Fujita & Takahara

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(1999a). Moreover, the major axis is found to describe the virial density of clusters (Fujita & Takahara 1999a).

3. Discussion

The above analysis raises two questions. The first question is why there is the fundamental plane. The behavior of the gas mass fraction ($f_{\rm gas}$) may be a clue to the question. For example, if we express $f_{\rm gas}$ with the virial mass ($M_{\rm vir}$) and density ($\rho_{\rm vir}$), $f_{\rm gas}$ turns out to be determined by

$$f_{\rm gas} \propto M_{\rm vir}^{0.4} \rho_{\rm vir}^{-0.1} \, . \tag{4}$$

This means that the baryon fraction in clusters is an increasing function of $M_{\rm vir}$. Such a relation of $f_{\rm gas}$ may be realized if supernovae in the galaxies or quasars heat the intracluster medium. In other words, the behavior of $f_{\rm gas}$ is likely to originate from the thermal history of clusters of galaxies (e.g. Fujita & Takahara 2000b).

The second question is why clusters form a two-parameter family. We think that one natural parameter is the virial mass of a cluster $M_{\rm vir}$. As another physically meaningful parameter, we may choose the virial density of a cluster $\rho_{\rm vir}$. We found that that $\rho_{\rm vir}$ is not constant and that it varies nearly independent of temperature (Fujita & Takahara 1999a). Since $\rho_{\rm vir}$ is supposed to reflect the critical density of the universe when the cluster, especially around the core region, collapsed, it suggests that the present day clusters consist of objects with a range of collapse redshift. Utilizing the spherical collapse model of cluster formation, and assuming that the cluster X-ray core radius is proportional to the virial radius at the time of the cluster collapse, we find that some of the clusters we investigated formed at $z > 1$. This result prefers a low-density universe ($\Omega_0 < 1$). Moreover, the double structure of dark matter distribution, which is observed in many clusters, may imply that the clusters collapse at least twice (Fujita & Takahara 2000a). We also find that the model of $n \sim -1$ is favorable (Fujita & Takahara 1999b), where n is the slope of initial fluctuation spectrum of the universe $P \propto k^n$.

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