Relations of Physical Properties for a Large Sample of X-Ray Galaxy Clusters

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Abstract. One hundred and six galaxy clusters have been studied in detail using X-ray data and important global physical properties have been determined. Correlations between these properties are studied with respect to the description of clusters as a self-similar class of objects. The results support the self-similar picture only partly and significant deviations are found for some correlations.

1. Introduction

Galaxy clusters are the largest collapsed objects in the Universe. Understanding the physical processes governing the formation of these enormous objects therefore represents an intriguing task. Relations between bulk properties of clusters provide an understanding of the underlying physics. There is now high quality X-ray data available for many clusters and recently many authors have studied cluster samples in order to search for such fundamental relations (e.g., Fukazawa 1997; Allen & Fabian 1998 (also these proceedings, atp); Arnaud & Evrard 1999; Ettori & Fabian 1999 (atp); Horner et al. 1999; Jones & Forman 1999; Mohr et al. 1999; Schindler 1999 (atp)).

We have constructed an X-ray flux-limited sample of the brightest clusters in the ROSAT All-Sky Survey (RASS) to determine the local cluster mass function (Reiprich 1998, Reiprich & Böhringer 1999a). This sample as well as some additionally included clusters not meeting the strict selection criteria represent a great opportunity to correlate the physical properties of nearby clusters. Here we give the preliminary results. Throughout $H_0 = h_50^{-1} 50 \text{ km/s/Mpc}, h_{50} = 1$, $q_0 = 0.5$ and $\Lambda = 0$ is used.

2. Data Reduction and Analysis

We used mainly high exposure ROSAT PSPC pointed observations to determine the surface brightness profiles of the clusters, excluding obvious point sources. If no pointed PSPC observations were available in the archive or if clusters were too large for the field of view of the PSPC we used RASS data. To calculate the gas density profiles the standard $\beta$-model (Cavaliere & Fusco-Femiano 1976), (Gorenstein et al. 1978) (Equ. 1) has been used.

$$\rho_{\text{gas}}(r) = \rho_{\text{gas}}(0) \left( 1 + \frac{r^2}{r_c^2} \right)^{-\frac{3}{2}-\beta}$$  (1)

$$S_X(R) = S_X(0) \left( 1 + \frac{R^2}{r_c^2} \right)^{-3\beta+\frac{1}{2}}$$  (2)

Fitting the corresponding surface brightness formula (Equ. 3) to the observed surface brightness profiles gives the parameters needed to derive the gas density profiles. To check if the often detected central excess emission (central surface brightness of a cluster exceeding the fit value) biases the mass determination we also fitted a double $\beta$-model of the form $S_X = S_{X_1} + S_{X_2}$ and calculated the gas mass profiles by $\rho_{\text{gas}} = \sqrt{\rho_{\text{gas}_1}^2 + \rho_{\text{gas}_2}^2}$. Comparison of the single and double $\beta$-model gas masses shows good agreement.

We compiled the values for the gas temperature ($T_{\text{gas}}$) from the literature, giving preference to temperatures measured by the ASCA satellite (Markevitch et al. 1998; Fukazawa 1997; Edge & Stewart 1991; David et al. 1993). For clusters for which we did not find a published temperature we used the X-ray luminosity-temperature relation given by Markevitch (1998).

Assuming hydrostatic equilibrium the gravitational masses for the clusters can be determined. Using the ideal gas equation, plugging Equ. 1 into the hydrostatic equation and assuming the intracluster gas to be isothermal yields the gravitational mass profile

$$M_{\text{tot}}(r) = \frac{3kT_{\text{gas}}r^3\beta}{\mu m_p G} \left( \frac{1}{r^2 + r_c^2} \right).$$  (3)

Having acquired the gravitational mass profiles for the clusters it is now important to determine the radius within which to determine the cluster mass. Simulations by Evrard et al. (1996) have shown that the assumption of hydrostatic equilibrium is generally valid within a radius, $r_{500}$, where the mean gravitational mass density is greater than or equal to 500 times the critical density $\rho_c = 4.7 \cdot 10^{-30} \text{g cm}^{-3}$, as long as clusters undergoing strong merger events are excluded. We calculated $M_{\text{tot}}$ at
3. Results

For correlations of the gas temperature with other quantities we exclude the 24 clusters whose temperatures have been estimated using the \( L_X - T_{\text{gas}} \) relation. Luminosities have been calculated in the energy range \( 0.1 - 2.4 \text{ keV} \). In Fig. 1 the \( L_X - T_{\text{gas}} \) relation for 82 clusters is shown. A linear regression fit yields \( L_X = 5.9 \cdot 10^{44} T_{\text{gas}}^{2.36} \), where \( L_X \) is in units of \( \text{erg s}^{-1} \) and \( T_{\text{gas}} \) in \( 6 \text{ keV} \). There is an indication of a steepening of the slope towards the lower temperatures. In Fig. 2 the \( M_{\text{gas}} - T_{\text{gas}} \) relation for 82 clusters is shown. A linear regression fit yields \( M_{\text{gas}} = 3.2 \cdot 10^{12} T_{\text{gas}}^{2.08} \), where \( M_{\text{gas}} \) is in solar units and \( T_{\text{gas}} \) in \( \text{keV} \). Also here a steeper slope for low \( T_{\text{gas}} \)-clusters is visible. The slope is less steep and the normalization much higher compared to the high redshift, high temperature sample of Schindler (1999). In Fig. 3 the \( M_{\text{tot}} - T_{\text{gas}} \) relation for 82 clusters is shown. A linear regression fit yields \( M_{\text{tot}} = 3.2 \cdot 10^{13} T_{\text{gas}}^{1.74} \), where \( M_{\text{tot}} \) is in solar units and \( T_{\text{gas}} \) in \( \text{keV} \). The slope is steeper and the normalization lower compared to the simulated clusters of Evrard et al. (1996). In Fig. 4 the \( L_X - M_{\text{gas}} \) relation for 106 clusters is shown. A linear regression fit yields \( L_X = 1.3 \cdot 10^{29} M_{\text{gas}}^{1.11} \), where \( L_X \) is in units of \( \text{erg s}^{-1} \) and \( M_{\text{gas}} \) in solar units. There is a subtle hint that high \( M_{\text{gas}} \)-clusters exhibit a steeper slope than ones with low \( M_{\text{gas}} \). In Fig. 5 the \( f_{\text{gas}} - M_{\text{tot}} \) relation for 106 clusters is shown. A linear regression fit yields \( f_{\text{gas}} = 6.2 \cdot 10^{-4} M_{\text{tot}}^{0.16} \), where \( f_{\text{gas}} \) (\( = M_{\text{gas}}/M_{\text{tot}} \), gas mass fraction) is unitless and \( M_{\text{tot}} \) in solar units. The slope of this relation depends on the relative number of lightweight clusters included, as can be seen from the fit of two power laws \( f_{\text{gas}1} \propto M_{\text{tot}}^{0.41} \), \( f_{\text{gas}2} \propto M_{\text{tot}}^{-0.05} \) for different mass ranges. In order to assess the radial distribution of the gas mass fractions compared to the mass of the clusters we have also determined the gas and gravitational masses within \( r_{500} \). If the ratio \( F_{2/5} = f_{\text{gas}}(r_{200})/f_{\text{gas}}(r_{500}) \) is greater than one, then the radial gas distribution is less steep than the dark matter distribution in the outer parts of the clusters. In Fig. 6 the \( F_{2/5} - M_{\text{tot}} \) relation for 106 clusters is shown. A linear regression fit yields \( F_{2/5} = 9.6 \cdot M_{\text{tot}}^{-0.06} \), where \( F_{2/5} \) is unitless and \( M_{\text{tot}} \) in solar units. The slope gets steeper with increasing \( M_{\text{tot}} \).

4. Discussion

In the previous section clear, tight correlations have been shown to exist between global physical parameters of galaxy clusters. How do these correlations compare to theoretical predictions and relations found by other authors? What can we infer from the measured relations?

Simple self-similar scaling laws predict \( T_{\text{gas}} \propto M_{\text{tot}}^{1.5} \) and \( L_X \propto T_{\text{gas}}^2 M_{\text{tot}} \) at a characteristic radius, e.g. \( r_{500} \), in the ROSAT energy band \( (0.1 - 2.4 \text{ keV}) \). In this self-similar picture \( f_{\text{gas}}(M_{\text{tot}}, T_{\text{gas}}) \) should be constant for all clusters. We find, however, \( f_{\text{gas}} \propto M_{\text{tot}}^{0.16} \) (Fig. 3) and \( f_{\text{gas}} \propto M_{\text{gas}}^{0.22} \) (graph not shown). We note the closer similarity to a broken power law shape, given in section 3.

The following derived simple theoretical relations often depend on \( f_{\text{gas}} \), therefore we give both, the values derived...
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with constant $f_{\text{gas}}$ and the values derived with the found dependencies of $f_{\text{gas}}$ on $M_{\text{tot}}, M_{\text{gas}}$ (in parentheses).

One derives $L_X \propto M_{\text{tot}}^{1.00 \pm 0.32}$, with 1.32 being consistent with the empirical $L_X - M_{\text{tot}}$ relation we have determined ($L_X = 3.3 \cdot 10^{26} M_{\odot}^{1.23}$; Reiprich & B"{o}hringer 1999b). With the above proportionality one finds $L_X \propto T_{\text{gas}}^{1.98}$, not very well in agreement with our measured result $L_X \propto T_{\text{gas}}^{2.01}$ (Fig. 4). Markevitch (1998) found $L_X \propto T_{\text{gas}}^{2.09}$. In his sample, however, no low temperature clusters are included ($T_{\text{gas}} \geq 3.5 \text{keV}$), which seem to steepen the relation slightly in our sample.

For the $M_{\text{gas}} - T_{\text{gas}}$ relation one would expect a proportionality like $M_{\text{gas}} \propto T_{\text{gas}}^{1.50}$, which does not compare well with our measured relation $M_{\text{gas}} \propto T_{\text{gas}}^{2.08}$ (Fig. 5). The gas mass is determined almost independently from the temperature, so this tight correlation indicates small intrinsic scatter. Our measurement is in agreement with Mohr et al. (1999) who found $M_{\text{gas}} \propto T_{\text{gas}}^{1.98}$. Schindler (1999) found for a sample of high redshift, high temperature clusters an exponent of $4.1 \pm 1.5$ and a factor of $\sim 100$ lower normalization. These large differences may indicate an evolutionary effect, in the sense that for $T_{\text{gas}} \lesssim 10 \text{keV}$ high redshift clusters have a higher temperature at the same gas mass. This interpretation is supported by the fact that Schindlers $L_X_{\text{bol}} - T_{\text{gas}}$ relation has a steeper slope than the same relation for nearby samples. But the uncertainties are too large for a final decision.

Our measured relation $M_{\text{tot}} \propto T_{\text{gas}}^{1.74}$ (Fig. 5) is steeper than the expected value of 1.5 for the exponent. A similar discrepancy has also been found by other authors (Mohr et al. 1999; Horner et al. 1999, using data of Fukazawa; Ettori & Fabian 1999), however, Horner et al. show for a sample of medium to high mass clusters that the discrepancy may be reconciled if measured $T_{\text{gas}}$ profiles are used to determine $M_{\text{tot}}$ (they used $r_{200}$). The normalization of the $M_{\text{tot}} - T_{\text{gas}}$ relation of the simulated clusters of Evrard et al. (1996) is a factor of $\sim 2$ higher than our measured normalization. In general one should keep in mind that $T_{\text{gas}}$ and $M_{\text{tot}}$ are not two independently measured quan-
ties (Eq. 3), which complicates the interpretation of the fitting result.

Scaling laws predict \( L_X \propto M_{\text{gas}}^{1.0(1.22)} \). We measure \( L_X \propto M_{\text{gas}}^{1.11} \) (Fig. 4), which is in reasonable agreement.

If clusters were exactly self-similar objects, the gas mass fraction at a characteristic radius should be constant for all clusters. Several authors have related measured values of \( f_{\text{gas}} \) and \( M_{\text{tot}} \) or \( T_{\text{gas}} \). Up to now there is not even qualitative agreement on the form of this relation. For example David et al. (1995) found indications for an increase of \( f_{\text{gas}} \) with increasing \( T_{\text{gas}} \), Allen & Fabian (1998) for a sample of X-ray luminous clusters found indications for a decrease of \( f_{\text{gas}} \) with increasing \( T_{\text{gas}} \); Ettori & Fabian (1999) found no dependence of \( f_{\text{gas}} \) on \( M_{\text{tot}} \) for high luminosity clusters, but instead found indications for a decrease of \( f_{\text{gas}} \) with increasing redshift. We find \( f_{\text{gas}} \propto M_{\text{tot}}^{16} \) (Fig. 3) but as noted earlier a simple power law description of this relation may not be very useful. The gas mass fraction stays fairly constant for \( M_{\text{tot}} \gtrsim 10^{14} M_\odot \) but seems to decrease strongly below this mass.

We next consider the gas mass fractions determined within two different characteristic radii (\( r_{500} \) and \( r_{200} \)) and relate the ratio of these two fractions to the gravitational mass. Fig. 5 exhibits several interesting features. A) The gas mass fractions are in general larger when measured within larger radii, as noted by previous authors (e.g., David et al. 1995). This means the gas distribution is flatter than the dark matter distribution in the outer parts of clusters. B) The increase of \( f_{\text{gas}} \) with radius gets smaller towards higher mass clusters. A qualitatively similar trend has also been found by Schindler (1999). C) For clusters with \( M_{\text{tot}} \gtrsim 10^{15} M_\odot \) the gas mass fractions seem to decrease with increasing radius. These features are qualitatively consistent with non-gravitational energy input affecting less massive groups/clusters more than massive clusters (e.g., supernova driven galactic winds). These features do not suggest a universal value for the gas mass fraction, \( f_{\text{gas}} \) rather seems to depend on radius and cluster mass. Feature C) indicates the possibility that estimates of \( \Omega \) based on extrapolation of \( f_{\text{gas}} \) within a specific cluster radius to the whole Universe may deserve reconsideration. For instance if the trend of decreasing gas mass fraction towards higher masses and therefore larger radii continues, \( \Omega \) may have been underestimated previously. But: it is not yet clear if one can draw significant conclusions from Fig. 5 since determination of masses within \( r_{200} \) generally requires extrapolation beyond the significantly measured cluster emission. Furthermore the hydrostatic assumption, fundamental for the gravitational mass estimate, may not always be justified at \( \sim r_{200} \). Therefore this relation should be considered as tentative. We are currently in the process of estimating the errors – which can be large since the gravitational mass plays a key role – in order to quantify the significance of the results.

5. Conclusions

1.) We find several tight correlations between physical parameters of a large sample of galaxy clusters.
2.) Not all of the slopes agree with expectations from simple self-similar scaling relations and some also cannot be made compatible if variations in the gas mass fractions are taken into account.
3.) Slight deviations from pure power laws are found. Except the weak bend in the \( L_X - M_{\text{gas}} \) relation they may qualitatively be explained by assuming that a non-gravitational energy input has taken place in clusters.
4.) Comparison to relations of high redshift clusters gives a weak indication for evolution, in the sense that clusters at high redshift have a higher gas temperature at a given gas mass.
5.) It is suggested that it may be difficult to assign a universal gas mass fraction to galaxy clusters, since the gas mass fraction seems to depend on radius and cluster mass.
6.) For massive clusters indications are found that the gas mass fraction decreases in the outer parts. If confirmed this may influence estimates of the baryon density in the Universe based on extrapolations from gas mass fractions on cluster scale to Universe scale.

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