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X-Ray Observations of Cluster Mergers Before 2000 AD

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Abstract. I review the evidence for cluster mergers from X-ray observations with *Einstein* and *ROSAT*. Different techniques to study cluster mergers via X-ray imaging and spectral data, and the current implications of measurements of cluster substructure for Ω_0, are briefly discussed.

1. Introduction

Today we take it for granted that many galaxy clusters exhibit substructure, and thus are in early stages of formation. This, of course, was not always the case. In the 1980s there were several searches for cluster substructure in the optical, but their results were controversial, primarily because of the difficulty in assessing the importance of projection effects and the statistical significance of substructure. The reality of substructure in clusters was firmly established with *ROSAT* observations in the early 1990s. The watershed example is that of A2256 which had long been thought to be a prototypical relaxed cluster when examined from the perspective of its galaxy isopleths. But the existence of a large subcluster near the cluster center was clearly displayed in the *ROSAT* PSPC image (Briel et al. 1991). *ROSAT* also clearly demonstrated significant subclustering in the Coma cluster (Briel, Henry, & Böhringer 1992) which was presumed to be the quintessential relaxed cluster. Hence, *ROSAT* images clearly established the existence of substructure in clusters, and thus showed that such clusters are really still forming.

2. Merger Frequency & Quantitative Morphology

The fundamental question raised by these early *ROSAT* observations is how widespread is merging in clusters? Are clusters generally young or old? Or is there an equal distribution of cluster ages in a given cluster sample? To address this issue one needs to have measurements of the subclustering properties of a large cluster sample and, of equal importance, a precise definition of the "dynamical age" of a cluster. The first systematic X-ray study of cluster merging was by Jones & Forman (1992). From visual inspection of ~ 200 *Einstein* cluster images, Jones & Forman separated the clusters into 6 morphological classes. These classes range from relaxed single-component systems to systems with a large degree of substructure. From the relative populations of these classes they deduced that $\sim 30\%$ of clusters have substructure, which is actually a lower limit because of the limited resolution of the *Einstein* IPC. This study established that

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merging and substructure are very common in clusters. Consequently, the need arose for a more precise assignment of the age of a cluster; e.g., how much older or younger are clusters in the Jones & Forman classes? Hence, Jones & Forman (1992) ushered in the era of quantitative X-ray cluster morphology.

2.1. Detailed Structural Decomposition

Quantitative studies of cluster X-ray morphologies have traveled down two distinctly different paths. The first path is that of the detailed structural analysis of clusters to determine the number of substructures, their fluxes, spatial properties, etc.. A popular approach is to examine the residuals obtained from subtracting a smooth model representing a relaxed cluster (usually an elliptical β model) from the X-ray cluster image (e.g., Davis 1994; Neumann & Böhringer 1997). A more general method is to perform a wavelet decomposition of the X-ray image which has been successfully applied to several clusters (e.g., Slezak et al. 1994; Grebenev et al. 1995; Pierre & Starck 1998; Arnaud et al. 2000).

2.2. Global Morphology Classification

The other path taken by studies of quantitative X-ray cluster morphology is to devise statistics to convert the morphology into some indicator of the cluster age. One successful method is that of the center-shift introduced by Mohr, Fabricant, & Geller (1993). Another set of morphology statistics is the "Power Ratios" of Buote & Tsai (1995). The Power Ratios (PRs) are constructed from moments of the two-dimensional gravitational potential computed within a circle of specified radius placed at the X-ray centroid. Since the X-ray image is used rather than a surface mass density map (such as produced by weak lensing), the PRs are really formed from moments of a pseudo-potential. The physical motivation behind the PRs is that they are related to potential fluctuations. And since it is thought that large potential fluctuations drive violent relaxation in clusters, the PRs are closely related to the dynamical state of a cluster (see Buote 1998).

From analysis of the brightest ~ 40 clusters with the *ROSAT* PSPC Buote & Tsai (1996) showed that the PRs represent a quantitative implementation of the Jones & Forman morphological classification scheme. It was shown quantitatively that the brightest ~ 40 clusters lack young members and are instead dominated by mostly evolved clusters with only small-scale (< 500 kpc) substructure. Hence, cooling flows are expected to dominate as has been suggested on different grounds (e.g., Arnaud 1988). In fact, it was also shown (Buote & Tsai 1996) that the PRs significantly correlate with the cooling flow mass deposition rate providing for the first time a quantitative description of the anti-correlation of substructure with the strength of a cooling flow. Analysis of this correlation and its large scatter for small cooling flows should shed light on how cooling flows are disrupted by mergers and are subsequently re-established.

2.3. High-Redshift Clusters

Unfortunately, because of the limited resolution and collecting area of *ROSAT* it has been difficult to study the morphologies of distant clusters. Two of the best examples ($z \sim 0.4$) are RXJ1347.5-1145 which appears to be a relaxed, cooling flow (Schindler et al. 1997) and Cl0024+17 which may have substantial

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substructure (Böhringer et al. 2000). These tantalizing glimpses demonstrate the need for a systematic study with *Chandra*.

3. Morphology & Cosmology

It is expected that clusters formed in a low-Ω_0 universe will be more evolved and have less substructure than clusters formed in a universe with $\Omega_0 = 1$ (Richstone, Loeb, & Turner 1992). N-Body simulations by several authors agree that center-shifts and PRs are sensitive to Ω_0 (Mohr et al. 1995; Buote & Xu 1997; Thomas et al. 1998). A simple semi-analytical approach suggests $P_2/P_0 \propto \Omega_0$ (Buote 1998). However, comparison of simulations to X-ray data have yielded different results depending on the simulations used (Mohr et al. 1995; Buote & Xu 1997; Valdarnini et al. 1999). All of the simulations have deficiencies. Either they did not include gas, did not have sufficient resolution, or did not have a sufficient number of clusters. Until appropriate simulations are applied to this problem we will not have a reliable constraint on Ω_0 from cluster morphologies.

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