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Using X-ray Images to Detect Substructure in a Sample of 40 Abell Clusters

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Using a method for constraining the dynamical state of a galaxy cluster by examining the moments of its X-ray surface brightness distribution, we determine the statistics of cluster substructure for a sample of 40 Abell clusters. Space considerations preclude a detailed discussion of the method here, so we include a brief summary and refer the reader to Mohr *et al.* (1992). Using X-ray observations from the *Einstein* Observatory Imaging Proportional Counter (IPC), we measure the first moment $M_1(\bar{r})$, the ellipsoidal orientation angle $\theta_2(\bar{r})$, and the axial ratio $\eta(\bar{r})$ at several different radii in the cluster. We determine the effects of systematics such as X-ray point source emission, telescope vignetting, Poisson noise, and characteristics of the IPC by measuring the same parameters on an ensemble of simulated cluster images. Due to the small band-pass of the IPC, the ICM emissivity is nearly independent of temperature (for 2 keV $\leq$ kT $\leq$ 8 keV), so the intensity at each point in the IPC images is simply proportional to the emission measure ($EM = \int n_e n_p \, dl$) calculated along the line of sight through the cluster (e.g. Fabricant *et al.* 1980). Therefore, barring a chance superposition of two X-ray emitting clusters[1], a significant variation in the image centroid $M_1(\bar{r})$ as a function of radius indicates that the center of mass of the intra-cluster medium (ICM) varies with radius. We argue that such a configuration (essentially an $m = 1$ component in the ICM density distribution) is a non-equilibrium component; it results from an off-center subclump or a recent merger in the ICM.

Our sample of 40 Abell clusters is made up of all clusters at $\bar{z} \leq 0.06$ with *Einstein* IPC observations with enough collected photons to apply the method. We characterize the sample in a statistical sense by comparing the distribution in velocity dispersions with the distribution determined from a group of 65 Abell clusters (Zabludoff *et al.* 1990). Our sample has more high dispersion clusters (>1400 km s^{-1}) and fewer low dispersion clusters (<500 km s^{-1}), but the general shape of the distributions is similar. The median velocity dispersion in the Zabludoff *et al.* sample is 744 km s^{-1}, while in our sample it is 853 km s^{-1}. Given the velocity dispersion-X-ray luminosity correlation, the bias in our sample toward high velocity dispersion systems is not surprising; the low dispersion clusters tend to have low X-ray fluxes and only yield good images with extended observation.

As briefly discussed above we make measurements on simulated images in order to determine the significance of the measured variations in the IPC image centroid $M_1(\bar{r})$. For this sample we declare the variations to be significant (the cluster has substructure) if $\leq$1% of the simulated images have measured variations which are larger than the variations in the real IPC image. With this criterion, 27 of the 40 clusters (68%) exhibit measurable departures from dynamical equilibrium, while 13 do not. It is important to note that failure to find an $m = 1$ component in the ICM in no way guarantees that the cluster is a relaxed, equilibrium system. Mergers in which the symmetry axis lies close to the line of sight would produce very little signal. Systematic effects and poor signal-to-noise images decrease our sensitivity. This point is well illustrated by Figure 1. We plot the distribution in number of image photons (a measure of the quality of the

[1] Using the measured $\log N - \log S$ distribution for clusters, ignoring clustering or anti-clustering on 30′ scales, and taking the mean scale of X-ray emission from clusters to be 30′ in radius, we calculate the probability of a superposition for a middle flux-range cluster like Abell 2256 to be <1%.

Figure 1: Image Quality

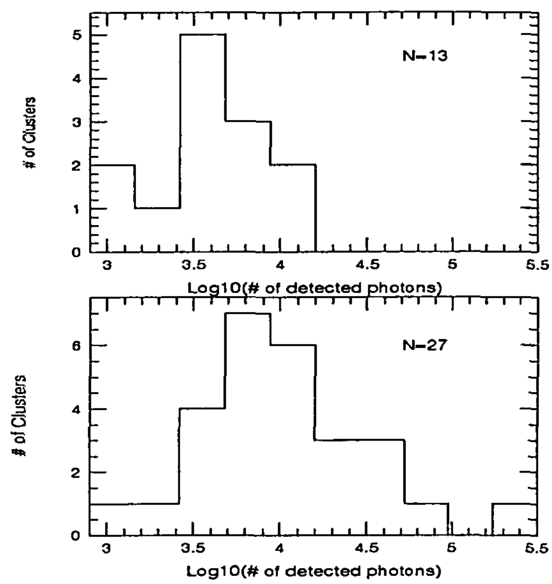

Figure 2: Velocity Dispersion

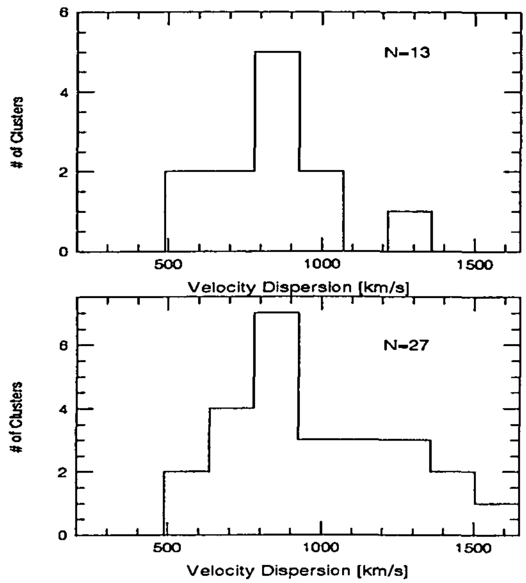

image) for the two cluster groups. The median number of counts in the group of 27 is 10,715, while the median number in the group of 13 is 4,046. Clearly, the clusters with the highest quality images tend to fall in the group of 27 with measured substructure. Therefore, we regard 68% as a lower limit to the actual fraction of clusters with measurable substructure. Further work on higher quality ROSAT images will allow a more sensitive examination of the clusters with poor *Einstein* images.

Although a full discussion of the characteristic differences between the two groups of clusters requires a longer paper, it is interesting to note (see Figure 2) that the clusters with high velocity dispersions (>1100 km s^{-1}) tend to be clusters with measurable substructure. One interpretation of this tendency is that the measured line of sight dispersions in these clusters are enhanced due to recent merger activities; if this is true, there may be considerable departures from an isotropic velocity dispersion in these systems which will complicate calculations of the cluster mass. Further investigation is required to substantiate this.

In summary, we present the results of a study of 40 Abell clusters using a method which examines the low order moments of the X-ray surface brightness profiles. We determine that $\geq$68% of the clusters in our sample have measureable substructure. This result is significant for several reasons: 1) the method is most sensitive to substructure in the core of clusters which are generally believed to be in virial equilibrium and 2) the higher sensitivity of the X-ray method yields a higher proportion of substructure than previous optical investigations.

References

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