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Morphological evolution of clusters

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SUMMARY

Recently Edge *et al.* have shown evidence for an evolution in the luminosity function of X-ray clusters at low redshift. We show that this can be explained as a transition from high Bautz–Morgan type clusters to low Bautz–Morgan type (with a dominant central galaxy). This interpretation is supported by the, albeit incomplete, data in cluster catalogues.

We show that different Bautz–Morgan types lie in different regions of the X-ray luminosity versus temperature diagram and suggest physical explanations for this distinction. High Bautz–Morgan type clusters seem to obey the constant, or maximum, core radius relation suggested by Edge *et al.* Low Bautz–Morgan types may have a constant, or maximum, core density. Alternatively the central galaxy halo may boost the X-ray flux.

1 INTRODUCTION

Rich clusters of galaxies are sites of strong, thermal X-ray emission from the hot gas contained within them and as such they provide a powerful diagnostic of the mass distribution of the Universe. X-ray surveys are free of the confusion surrounding optical cluster searches where foreground and background galaxies (plus projection effects and absorption) hamper identification. Recently Edge *et al.* (1990) have presented a flux limited sample of X-ray clusters in which they recognize evolution in the luminosity function, with a deficit of bright clusters between the redshifts of 0.1 and 0.2.

We take this sample and find the Bautz–Morgan type (hereafter BM type) for all the clusters so classified (Bautz & Morgan 1970; mainly Abell, Corwin & Olowin 1989; also Leir and van den Bergh 1977, hereafter LvB). Clusters are given a Bautz–Morgan type depending on the magnitude difference between the brightest and second brightest cluster member. Clusters with a large magnitude difference get a low BM type (I, I–II) and contain a single, large, central dominant (hereafter cd) galaxy. High BM type (II, II–III and III) clusters have no cd galaxy. Of the 55 clusters in the Edge *et al.* sample 47 have BM types, listed in Table 1. Of the remainder, five are close to the galactic plane (and suffer from optical absorption), two do not have Abell numbers and the other is an untyped Abell cluster. We find a strong correlation between BM type and flux leading us to conclude that either the sample is incomplete (highly deficient in BM type I, I–II at redshifts of 0.1–0.2) or that the clusters are evolving at recent epochs from type III's to type I's. The long known correlation between luminosity and temperature (Mushotzky 1984) becomes two much tighter correlations when BM types are discriminated.

The evolution in BM type should not be limited to X-ray bright clusters. We therefore look for, and find, a correlation between BM type and redshift in the Abell catalogue: there are many more type I's and I–II's at low redshift than expected. These results are strongly supported by examining BM type and Abell's distance indicator (Abell 1958).

The morphological evolution from BM-type III to BM-type I is caused by the formation of a cd galaxy. This could be due either to collisions between the far more common BM type III's, forming BM type I clusters, or the merger of several galaxies within the core of a single BM type III. We show that the X-ray properties of the low BM type clusters are consistent with a constant, maximum density for the cluster core. The high BM type clusters are likewise consistent with the constant (maximum) core radius suggestion of Edge *et al.* Alternatively the difference beween the two may be due to the excess emission from the central cd galaxy halo and associated cooling flow.

2 BM TYPE AND FLUX

In Fig. 1 we plot the cumulative number against 2–10 keV flux for the X-ray cluster sample of Edge *et al.* If the sample is truly complete and the cluster morphology is not evolving then both low and high BM types should produce similar curves of slope $-3/2$ on a log–log plot (Euclidean geometry dominates at low redshift): this is not the case. A Kolmogorov–Smirnov test gives a 10 per cent probability that these are consistent with being drawn from the same distribution. An exactly analogous result has already been noted for the radio properties of clusters (Gubanov 1988, fig. 5). Although the small numbers cause some fluctuation, the high BM type clusters lie close to the Euclidean prediction; how-

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Table 1. Bautz–Morgan types for the clusters from the Edge *et al.* (1990) sample, arranged in order of decreasing flux.

Cluster	Bautz-Morgan Type
A426	II-III
Ophiuchus	
Virgo	III
Coma (A1656)	II
A2319	II-III
A3571	I
Centaurus (A3526)	I-II
Triang. Aust.	
3C129	
AWM7	
A754	I-II
A2029	I
A2142	II
A2199	I
A3667	I-II
A478	
A85	I
A3266	I-II
A401	I
0745-19	
A496	I
A1795	I
A2256	I-II
Cygnus-A	I
0336+09	
A1060	III
A3558	I
A644	III
A1651	I-II
A3562	I
A1367	II-III
A399	I-II
A2147	III
A119	II-III
A3158	I-II
Hydra-A	I
A2065	III
A2052	I-II
A2063	II
A1644	II
Klemona44 (A4049)	III
A262	III
A2204	II
A2597	III
A1650	I-II
A3112	I
A3532	II-III
A4059	I
A3395	II
MKW3s	
A1689	II-III
A576	III
A2244	I-II
A2255	II-III
A1736	III

ever, the low BM types have a very skewed distribution, with a large deficiency at low flux and they deviate from this relation at below the 1 per cent level. This suggests that the more condensed low BM types may have been missed in the surveys used to compile the sample of Edge *et al.* possibly being mistaken for active galactic nuclei (AGN's) or other compact sources, an effect which would become more pro-

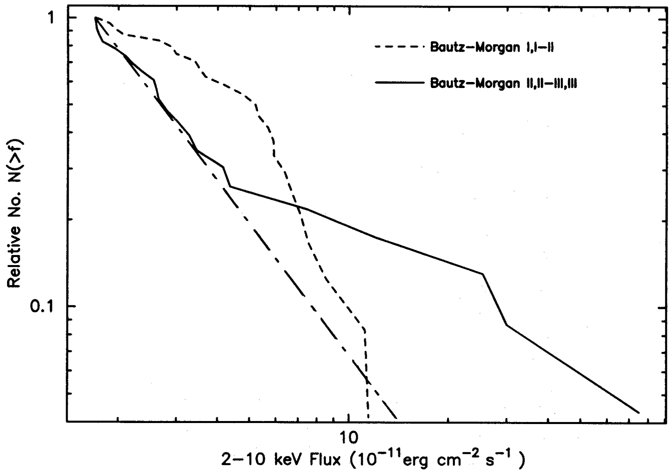

Figure 1. Flux (10^{-11} erg cm^{-2} s^{-1}) against cumulative number fraction of clusters which exceed this flux for low and high Bautz–Morgan types. There are 24 and 23 clusters of each kind, respctively. This is a log–log plot so each of the lines should have the Euclidean slope of $-3/2$ (shown) if no evolution is occurring and the counts are complete.

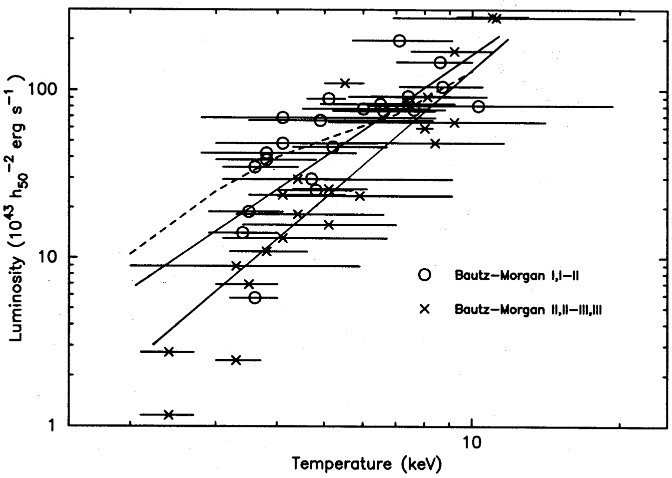

Figure 2. Temperature (keV) against luminosity (10^{43} h_{50}^{-2} erg s^{-1}) for the Edge *et al.* (1990) sample with Bautz–Morgan types discriminated. The two lines have slopes of 2 and 2.5 corresponding to constant density and constant radius, respectively. The dashed line shows the model discussed in Section 5.

ever, as most of the sample are well observed optically, compact clusters and AGN's have completely different spectra, and Abell clusters were the primary candidates for the unknown sources (Edge, private communication), widespread misidentification would seem unlikely. A more interesting possibility is that the type III's are evolving into type I's at recent times, simply explaining the lack of type I's at higher redshift.

3 LUMINOSITY AND TEMPERATURE

The correlation between luminosity and temperature for X-ray clusters (Fig. 2) has been known for several years (Mushotzky 1984). At the temperatures we are considering the emission from X-ray clusters is principally due to thermal bremsstrahlung (line emission becomes important at lower temperatures). The luminosity, L, which is dominated by the core of the cluster (Jones & Forman 1984), is related to the core radius of the system, a, the central density, ρ_0, and the temperature, T, by the proportionality:

$$L \propto \rho_0^2 a^3 T^{1/2} \propto \rho_0^{1/2} T^2 \propto \frac{T^{2.5}}{a}, \tag{1}$$

where we have used the virial relation $\rho_0 a^2 \propto T$. For constant density clusters, $L \propto T^2$, whilst a constant core radius gives $L \propto T^{2.5}$.

Unfortunately, the scatter in the luminosity-temperature plane does not allow us to rule out either of these models, although the constant density relationship looks unlikely. However, if BM type is added to this plot then two distinct relations appear; the lines shown are $L \propto T^2$ and $L \propto T^{2.5}$. The best fit slopes to the two sets of data are 1.78 ± 0.55 and 2.94 ± 0.45 for low and high BM types respectively. The two cluster types occupy different regions on the plane that overlap at high luminosity. Both these correlations are significantly tighter than the previous best fit to the data. The remaining untyped clusters appear to be mainly of low BM type except for 3C129 and AWM7 which lie on the high BM type line. All but one $(0745-19)$ of the untyped clusters are at a redshift of less than 0.1 with six closer than $z = 0.06$, so any prevalence of type I's amongst these would further reinforce the excess of low BM types nearby.

Several clusters appear to be mistyped in the BM catalogue. For example Perseus (A426) lies well above the best fit line for the high BM types but is typed II–III in the catalogue despite a central cD galaxy which dominates the X-ray emission. In addition many of the low temperature clusters lie below the best fit lines because much of their emission lies outside the 2–10 keV flux band.

4 BM TYPE AND DISTANCE

As the X-ray data suggest evolution in morphological type we look for a similar result in all clusters. Using the 482 clusters in the Northern Abell Catalogue which have both a quoted redshift and a BM type we obtained the results in Table 2. There appears to be an excess of low BM type clusters nearby. The ratio of nearby low BM type clusters to nearby high BM type clusters is approximately 1:4, if we assume near completeness to this redshift (unlikely), then the equivalent ratio at higher redshift is 1:15. We can think of several selection effects that could affect this result, such as a tendency to measure the redshifts of nearby low BM type clusters preferentially, or a large number of misclassified clusters. Whatever the possible selection effects, they would need to be large to counteract the strong signal from the data.

Table 2. By column, the Bautz–Morgan type, the number of typed clusters in the Northern Abell Catalogue, the number of typed clusters in the Southern Abell Catalogue, the number of typed clusters in the north for which a redshift has been measured, and these redshifts split into three distance groups.

BM type	North	(South)	No. redshift	$z < 0.1$	$0.1 < z < 0.2$	$z > 0.2$
I	70	(126)	35	21	13	1
I-II	77	(254)	36	23	11	2
II	274	(248)	81	48	30	3
II-III	424	(366)	121	50	53	18
III	1086	(360)	209	93	87	29

Note that there is a discrepancy in the assignment of BM type between the Northern and Southern Abell Catalogues despite the fact that the majority of the classifications were made by the same group (Abell, Corwin & Olowin 1989). The discrepancy is probably due to the different plates used for the Southern Survey; more cD's are found in the Southern IIIa–J plates, which go deeper and have a finer grain than the 103a–E plates used for the Northern Survey. Very few redshifts have been measured for clusters in the southern hemisphere making it impossible to check the result there. We would expect the low BM types to be over-represented at higher redshift as they should be much easier to identify, surrounding a large, luminous galaxy, although it has been suggested (Kristian, Sandgate & Westphal 1978) that the opposite effect will occur as, for the high BM types, there will be several equally bright galaxies close together.

To check the suspected evolution in BM type we look at the Abell Distance Indicator, which is based on the magnitude of the tenth-brightest cluster member. Nearby clusters are given a low number, whilst long-range clusters have a high number (in the range 0–7). Despite the known problems with the catalogue we hope that the large numbers will swamp any individual misclassifications. The results of this approach are shown in Table 3: once again there is an excess of low BM type clusters nearby. The northern data has previously been derived by LvB who suggest that the cD envelopes disappear at high redshift due to K-dimming; their extended envelopes may also drop below the plate limit.

Clearly the cluster catalogues are incomplete, but for the above results to change significantly we would require a very large bias in the morphological type of the missing clusters. For example, almost all of the missing southern clusters of distance class 5–6 would need to be type I's.

5 DISCUSSION

We have shown that low and high BM types are separated on the luminosity versus temperature (L–T) diagram, presum-

Table 3. Abell Distance Indicator against Bautz–Morgan type for the Northern and Southern Abell Catalogues. The last row in each section is the ratio of low distance-indicator clusters to high distance-indicator clusters for each Bautz–Morgan type.

Dist.Ind.	Bautz-Morgan Type				
	I	I-II	II	II-III	III
North					
0+1+2	2	1	6	6	12
3	7	6	11	16	33
4	10	11	23	21	55
5	23	32	126	173	399
6	29	27	109	209	587
$\frac{0+1+2+3+4}{5+6}$	.37	.31	.17	.11	.10
South					
0+1+2	5	3	2	2	1
3	12	13	7	1	4
4	13	28	25	9	10
5	55	90	88	111	99
6	42	126	127	244	247
$\frac{0+1+2+3+4}{5+6}$	.31	.20	.16	.034	.043

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ably because the cd galaxy enhances the X-ray emission in low BM types.

The high BM type clusters lie close to the constant core radius relation previously suggested by Edge *et al.* It would also be valid to interpret this line as a boundary for clusters on the L–T plane in which case it would represent a maximum core radius. The physical reason for this is not obvious. As there is no single dominant galaxy the explanation presumably depends upon the smoothed properties of the cluster.

Similarly we can interpret the upper edge of the L–T relation as a constant core density for low BM type clusters, or as a maximum core density for the clusters as a whole. Alternatively, excess emission from the cd galaxy and its surrounding halo may boost the luminosity of the cluster, moving it from one relation to the other. One such model is shown as a dotted line on the L–T diagram. This includes the excess emission generated by a massive central halo of 10^{11} $M_\odot$ kpc^{-1} as has been invoked by Thomas, Fabian & Nulsen (1987) to explain the surface brightness distribution of the X-ray data. This excess emission is indicative of a cooling flow, which, while they can exist in the absence of a central halo, do always seem to be associated with a cd galaxy (Fabian, Nulsen & Canizares 1984).

We examined several other candidate statistics for a correlation with luminosity. None are particularly rewarding, due to the large uncertainties in the data. For the core radius (Sarazin 1986) the low BM types have a smaller mean size than the high BM types (Jones & Forman 1984), and the velocity dispersion is weakly correlated with temperature (Quintana & Melnick 1982). However, neither the harmonic mean radius (Hickson 1977), the Abell number count (Abell 1958) nor the Zwicky number (Zwicky, Herzog & Wild 1961) display any obvious correlation with either temperature, luminosity or morphology.

The scarcity of high luminosity clusters at redshifts greater than 0.1 was taken by Edge *et al.* to indicate significant, recent evolution in the cluster luminosity function. They produced a model in which mergers take place at constant core radius giving $L \propto T^{2.5}$. We suggest that these mergers result in the formation of a cd galaxy, changing the BM type from high to low and boosting the X-ray luminosity. This conclusion is supported by the incomplete data from galaxy catalogues. There are many more high than low BM type clusters so it is not necessary to invoke significant evolution in number density in this scenario.

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