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HUDDLED MASSES YEARNING TO STREAM FREE: GLOBULAR CLUSTERS IN THE HEARTS OF GALAXY CLUSTERS

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Extremely rich populations of globular clusters, numbering ten thousand or more, surround the central giant galaxies in rich clusters. I discuss some recent spectroscopic and photometric observations of these rich globular clusters populations. In very nearby galaxy clusters, the globular cluster velocities can be used to trace the transition from the galaxy potential to the larger cluster potential. Beyond $cz \approx 3000$ km s^{-1}, the globulars are too faint for spectroscopic studies with even the largest telescopes and cease to be useful dynamical tracers. However, the spatial distribution and size of the globular population also contains information on the central mass distribution of the cluster and can be measured out to $cz \gtrsim 20{,}000$ km s^{-1}. Overall, the data suggest that these rich globular cluster populations are comprised of normal, old globulars, the majority of which were assembled in the cluster centers before most of the stars in the cD galaxy were formed.

1 Introduction: Globular Clusters and their Uses

Globular clusters (GCs) provide key information for a wide variety of areas in astrophysics and cosmology. Absolute GC ages (see reviews by Salaris et al. [1997] and Chaboyer et al. [1999]) constrain the cosmological model by setting a lower bound on the age of the universe. The observed GC age range (e.g., Stetson et al. 1996; Sarajedini et al. 1997) constrains the time-scale of galaxy formation, and the distribution in metallicity can provide further details on the formation processes (e.g., Ashman & Zepf 1992; Ajhar et al. 1994; Forbes et al. 1997).

Globular clusters are also an important part of the distance scale. Their horizontal-branch magnitude is the basis for the "Population II" RR Lyra distances within our Galaxy (e.g., Carney et al. 1992; Carretta et al. 2000) and provides an important self-consistency check (e.g., Walker 1992; Ajhar et al. 1996; Fusi Pecci et al. 1996) of the Cepheid distance scale on which most extragalactic distances are based. In addition, the mean luminosity of the GCs in external galaxies has been used extensively as a standard-candle distance indicator reaching as far as the Coma cluster (e.g., Harris 1991; Baum et al. 1995, 1997; Whitmore et al. 1995; Kavelaars et al. 2000; Ferrarese et al. 2000).

Besides these other, more traditional, "uses," globular clusters are now recognized as unique and important probes of the centers of galaxy clusters. The present paper summarizes some recent work on this topic.

2 Globular Clusters as Kinematical Tracers of the Cluster Potential

The existence of massive dark halos around spiral galaxies has been known for over 20 years (Rubin et al. 1978) from their flat rotation curves. The presence of a dominant dark matter component in galaxy clusters has been known even longer from the galaxy dynamics (Zwicky 1937), and repeatedly confirmed by X-ray, lensing, and other dynamical studies. Yet, massive dark halos around individual giant ellipticals have been notoriously difficult to demonstrate and measure. The stellar velocity dispersion can only be traced to $\sim$ 10 kpc, roughly 20% of the distance to which spiral rotation curves can be followed, and then it becomes necessary to resort to various, usually sparse, tracers of the halo potential. For the same reason, the mass distribution in cluster cores is poorly constrained at radii $r \approx$ 10–50 kpc.

A major step forward came with the work of Cohen & Ryzhov (1997), who used the 10-m Keck telescope to measure velocities for 205 confirmed GCs around M87, the giant elliptical at the dynamical center of the Virgo cluster. Velocities for an additional 16 GCs were added by Cohen (2000). These authors found that the 1-d velocity dispersion of the M87 GC population rises from $\sigma \approx 300$ km s^{-1} at $r \approx 6$ kpc to $\sigma > 450$ km s^{-1} at $r > 30$ kpc (assuming the Virgo Cepheid distance of 16 Mpc, so that $1' = 4.7$ kpc). Interestingly, the rotation also increases outward from the center, reaching $v_{\rm rot} \approx 300$ km s^{-1} (Cohen 2000). Cohen & Ryzhov concluded that the total mass increases as $M(<r) \sim r^{1.7}$, or $\rho \sim r^{-1.3}$, which agrees well with the mass profile inferred from X-ray data (Nulsen & Böhringer 1995) in the region of overlap. A similar result was found by Romanowsky & Kochanek (2000), who determined the mass profile using joint constraints from the GCs and halo stars and concluded that the potential of the Virgo cluster is dominant by $r \approx 20$ kpc. Thus, the GC velocity data trace the transition from the dynamics of the M87 stellar halo to that of surrounding Virgo cluster.

Kissler-Patig et al. (1999) studied a sample of 74 GC velocities around NGC 1399, the central cD galaxy in the Fornax cluster ($d \approx 19$ Mpc), using data drawn from three previous spectroscopic studies. They also found a rising velocity dispersion profile, bridging the "velocity gap" between the NGC 1399 stellar halo and the galaxy population of the Fornax cluster. These authors concluded that most of the extended population of GCs were stripped from other Fornax galaxies, as advocated by Côté et al. (1998).

Recently, a team led by R. Sharples at Durham (Sharples et al. 1997; Beasley et al. 2000) and another from Caltech (J. Cohen, P. Côté, and myself) have obtained velocity data for large samples of GCs around NGC 4472. Although NGC 4472 is not a central cluster galaxy, it is the brightest Virgo member and the center of its own smaller subcluster $\sim$1 Mpc away from M87 in projection. It has also been the subject of a very detailed photometric study using Washington photometry (Geisler et al. 1996). The GC system contains two unusually well demarcated metallicity subpopulations, as compared to most other giant ellipticals (e.g., Gebhardt & Kissler-Patig 1999; Woodworth & Harris 2000; Brodie et al. 2000).

Figure 1 compares the velocity dispersion data for 272 NGC 4472 GCs, split into blue and red subpopulations following Geisler et al. (1996), to that of the stellar halo and the satellite galaxy population. The red GCs share the kinematics of, and have colors similar to, the stellar halo, bespeaking a common origin. The blue GCs have a significantly higher dispersion and show the transition to the dynamics of galaxy population. The blue population is also more extended in its spatial distribution. However, both subpopulations appear equally old, within the uncertainties (Beasley et al. 2000), and the same is true in M87 (Cohen et al. 1998).

Although it appears universally true that blue GC populations have more spatially extended distributions, it is unclear whether or not the striking difference in the dynamics of the two subpopulations is a common feature of the GCs around central cluster galaxies. There is no evidence for this effect in the available M87 GC data (Cohen et al. 1998), but the sample was not so clearly separated into blue and red components. In NGC 1399, the sample size is too

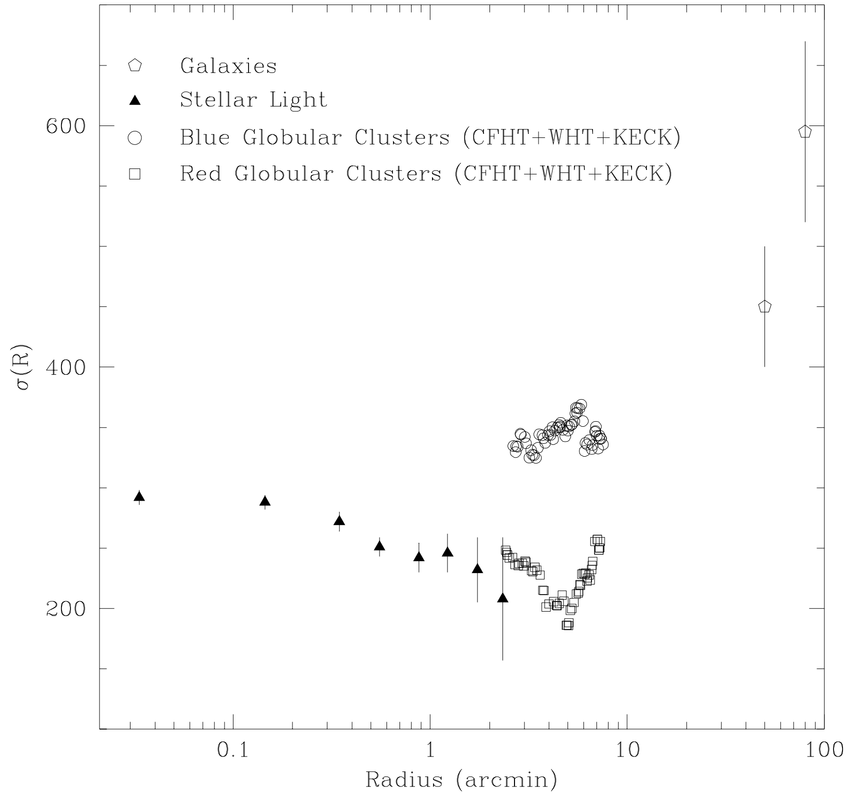

Figure 1: A comparison of the velocity dispersion profiles for 166 blue and 106 red globular clusters in NGC 4472 (data from the Caltech and Durham groups) to that of the stellar light (from Fisher et al. 1995) and satellite galaxies (from NED). The data points for the GCs are not all independent but show a heavily over-sampled running average to produce a smooth profile. While the red GC population is kinematically (as well as spatially and chemically) similar to the stellar halo, the more spatially-extended blue GC population traces the transition from the galaxy to the cluster potential.

small in to constitute a reliable test. Further spectroscopic observations in these two important systems are needed. Velocity measurements for the brightest GCs around the Hydra cluster cD NGC 3311, a giant galaxy with a very diffuse cD halo and a broad GC color distribution lacking any apparent multiple peaks (Brodie et al. 2000), would be extremely valuable and is now feasible with the VLT.

3 Globular Cluster Number as a Mass Tracer

At distances much beyond the Virgo and Fornax clusters, it becomes increasingly difficult to measure accurate velocities for individual GCs. For instance, at $cz \sim 3500$ km s^{-1}, the very brightest GCs have an apparent magnitude $V \sim 22.6$, requiring very long integrations to obtain adequate signal in the absorption line spectra. However, abundant GC populations can be photometrically detected around bright galaxies to many times this distance, and their properties contain useful information on the host galaxies and galaxy clusters.

3.1 Measuring GC Specific Frequencies

The globular cluster "specific frequency" S_N of a galaxy is the number of GCs per unit $M_V = -15$ of galaxy luminosity (Harris & van den Bergh 1981). Thus, a dwarf galaxy with $M_V = -15$ and a single GC would have $S_N = 1$. Spiral galaxies such as the Milky Way or M31 typically have $S_N = 0.5$–1, while most ellipticals have $S_N = 2$–4. However, cD galaxies such as M87 can have $S_N \approx 12$, which means a total GC population of $N_{\rm GC} \approx 12{,}500$ (see the review by Harris 1991). However, data on other such "high-S_N" systems were very sparse, as the total number of GCs is difficult to estimate from GC counts if the data do not approach the turnover magnitude m^0 of the globular cluster luminosity function (GCLF). At the distance of the Coma cluster, the GCLF has a V-band turnover $m_V^0 \approx 27.5$.

To address this problem, we (Blakeslee & Tonry 1995) developed a new method for simultaneously measuring specific frequencies and GCLF widths in relatively distant galaxies without the requirement of complete point source detection to the GCLF turnover. The method borrows from the surface brightness fluctuations (SBF) method (Tonry & Schneider 1988) for measuring galaxy distances. In the standard SBF technique, the fluctuations produced by the Poisson statistics of stars in an early-type galaxy are used to derive an average flux for the stellar population, yielding the distance (see the recent review by Blakeslee, Ajhar, & Tonry 1999). Here, we apply the same analysis methods to measure the fluctuations from unresolved GCs around more distant galaxies.

The usual way of determining S_N in galaxies beyond Virgo is to count the brightest GCs and extrapolate, yielding a result which is strongly dependent upon the assumed GCLF width σ. In our technique, we also first identify and count the brightest GCs, determining S_N as a function of σ, but we then excise these bright ones and measure the psf-convolved variance ("fluctuations") in the image from the rest of the GC population. This variance is directly proportional to the number density of remaining GCs; thus, we again determine S_N as function of σ. These two determinations will be consistent over some range in σ which should encompass the true value. Figure 2 provides an illustration. Even if there is relatively little variation in the GCLF σ among cD galaxies, the combined information from the counts of the brightest GCs and the variance from the fainter ones produces much tighter constraints on the total GC number.

3.2 Ground-based Suveys and Interpretations

We studied two different samples of GC populations in Abell cluster central galaxies using this new method. The first was a statistically complete sample of 19 northern clusters with early-type brightest members within $cz < 10{,}000$ km s^{-1} observed with the 2.4-m telescope at MDM Observatory on Kitt Peak (Blakeslee et al. 1997). The second was a smaller sample of more massive clusters to twice this distance with Keck (Blakeslee 1999). In all, S_N values were measured for 32 bright galaxies in 25 clusters. Figure 3 shows data for the most distant cluster studied, A2124 at z=0.066, which also happens to be the nearest cluster in which strong gravitational lensing of distant galaxy has been observed (Blakeslee & Metzger 1999)

The data show that S_N for central cluster galaxies correlates well with overall cluster properties including velocity dispersion and X-ray luminosity (see Figure 4), as well as other measures of cluster richness. In fact, the luminosities of the cD galaxies show relatively little variation (e.g., Postman & Lauer 1995), so the correlations exhibited in Figure 4 are really between the total number of GCs in the cluster center and the mass of the cluster. Luminous galaxies displaced from the cluster dynamical centers do not seem to participate in these correlations (although see Woodworth & Harris 2000).

We have argued (Blakeslee et al. 1997; Blakeslee 1999) that the observations are most easily explained if the GCs surrounding cD galaxies formed at early times and with an approximately universal efficiency of roughly 0.7 GC per $10^9\,M_\odot$. However, the present-day galaxy luminosity is fairly insensitive to this quantity, resulting in the observed correlations of GC frequency with cluster density. Thus, rather than having anomalously large GC populations, the galaxies are simply underluminous for their prominent positions in the centers of very rich clusters. In

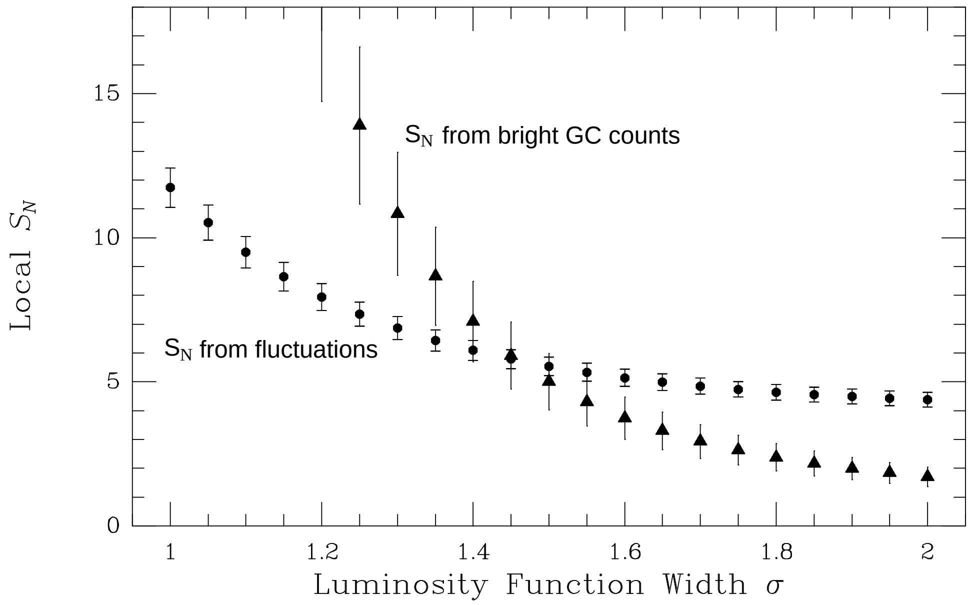

Figure 2: An illustration of the joint S_N-GCLF constraints using our count-fluctuation method. The figure shows S_N values for the Coma cD NGC 4874 at a radius $r \sim 1'$, as derived from point-source counts (triangles) and the power-spectrum of the surface brightness distribution ("fluctuations", circles) after removal of the detected point sources. Both measurements must be corrected for background contamination to yield the contributions from bright and faint GCs, respectively. Plotted errorbars include only measurement error and background uncertainty. The counts are much more sensitive to the assumed GCLF width σ because they represent only the bright tail of the luminosity distribution. The two types of measurement yield consistent values of $S_N \approx 6$ for $\sigma \approx 1.45$ mag (data from Blakeslee & Tonry 1995).

this "missing light" scenario, the gas is removed from the central galaxy into the intracluster medium at the cluster formation epoch, halting any subsequent star formation in the central galaxy that would serve to lower S_N. A similar model has been discussed by Harris et al. (1998), and McLaughlin (1999) has shown that the numbers work out in detail for the amount of gas surrounding the nearby galaxies M87, NGC 1399, and NGC 4472.

Blakeslee (1999) suggested that there may be evidence for later S_N evolution in these systems: the central galaxies in the more spiral-rich, less evolved clusters had marginally higher GC specific frequencies than those in the more centrally concentrated, spiral-poor clusters. Again the difference in the S_N values was because of the lower luminosities of the central galaxies in the less evolved clusters, not because of larger GC populations of in the more evolved one. Thus, continuing star formation and dynamical evolution in the spiral-rich clusters may allow the central galaxy to grow in luminosity, without adding large numbers of new GCs; the net result is a decrease in GC frequency. Following McLaughlin et al. (1994), who made a similar suggestion from a smaller, much less homogeneous, dataset, we call this process "S_N dilution." It will be interesting to see if this effect proves true; for now, the evidence is inconclusive.

3.3 Recent HST Data

Of course, with *HST*, it is possible to reach the GCLF turnover at the distance of the Coma cluster and obtain a more direct estimate of S_N. No one has yet done a systematic study of GC populations in a large sample of cD galaxies in rich clusters using *HST*, as the required integration times are substantial. However, Harris et al. (2000) have recently used *HST* to measure $S_N \approx 4$ for NGC 4874 in Coma. This is significantly lower than our value of $S_N = 9 \pm 2$

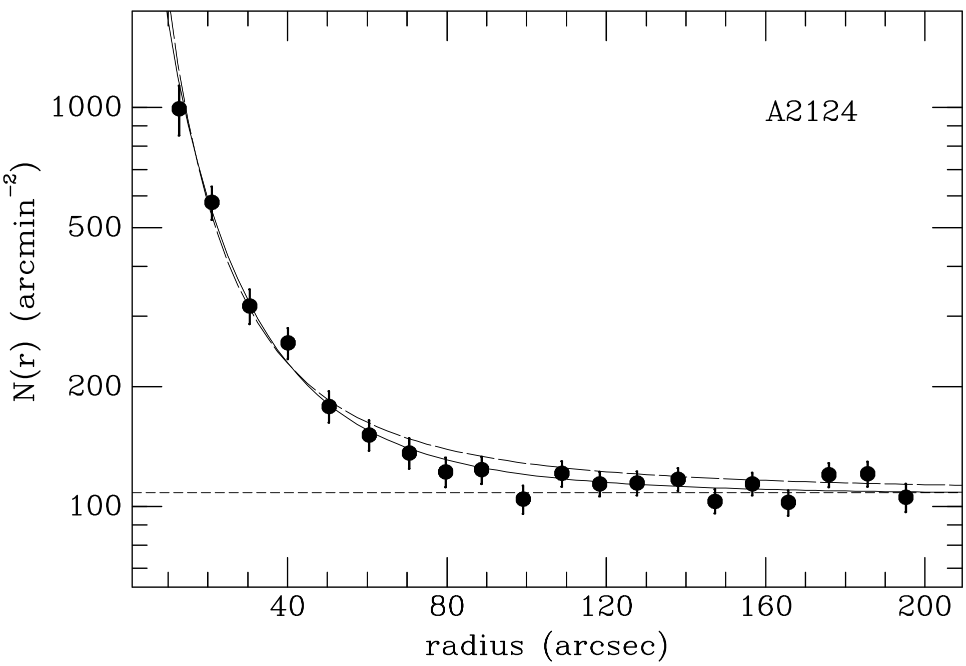

Figure 3: The incompleteness-corrected surface density of point sources in the extinction-corrected R magnitude range $23.6 \leq m_R \leq 26.6$ around the central cD galaxy in A2124 at $z = 0.066$ ($1' = 52\ h^{-1}$ kpc) (Blakeslee 1999). The solid and long-dashed curves represent de Vaucouleurs $r^{1/4}$ law and power-law fits, respectively, while the short-dashed line is the estimated background. The GC population is detected to at least $r \approx 150$ kpc ($h = 0.7$).

(Blakeslee et al. 1997). There are two basic reasons for this. First, they assumed a distance modulus 0.35 mag greater than ours, and this translates directly into a $\sim 35\%$ difference in S_N. Harris et al. point out that there is very close agreement between the observed GC counts when compared over the same radial and magnitude ranges. For instance, if the value of S_N at $r \sim 1'$ shown in Figure 2 above is transformed to their distance scale, we obtain very close agreement with $S_N \approx 4$.

The more important difference stems from the radial profiles measured in the two studies. We found that the GC distribution was more extended than the halo light, so that S_N increased with radius, yielding a significantly higher S_N. Harris et al. also found a very extended distribution in the inner parts, but then a sharp truncation of the GC system at $r \approx 2$ arcmin. It is most likely that problems with background source contamination or the I-band surface photometry at large radii (the rest of our data were all taken in the R-band, where the sky is much darker and CCD's flatten better, to avoid this problem) have affected the ground-based S_N measurement. Still, the sharp truncation found near the limit of the *HST* data is difficult to understand. It would be worth revisiting this system with the next generation of *HST* imaging cameras (ACS, WFC3) and their much wider fields of view.

4 Summary

The rich globular cluster populations at the centers of galaxy clusters constitute important probes of the central cluster potential. In nearby clusters, they can be used to directly trace the transition from the potential of the central galaxy to that of surrounding cluster. In the case of NGC 4472, the brightest Virgo elliptical, this transition is well traced by the more spatially-extended blue GC subpopulation, whereas the red GCs appear to share the dynamics of the stellar halo. By obtaining large samples of GC velocities around both central and non-central giant ellipticals, it will be possible to determine the mass profiles of the galaxies and constrain

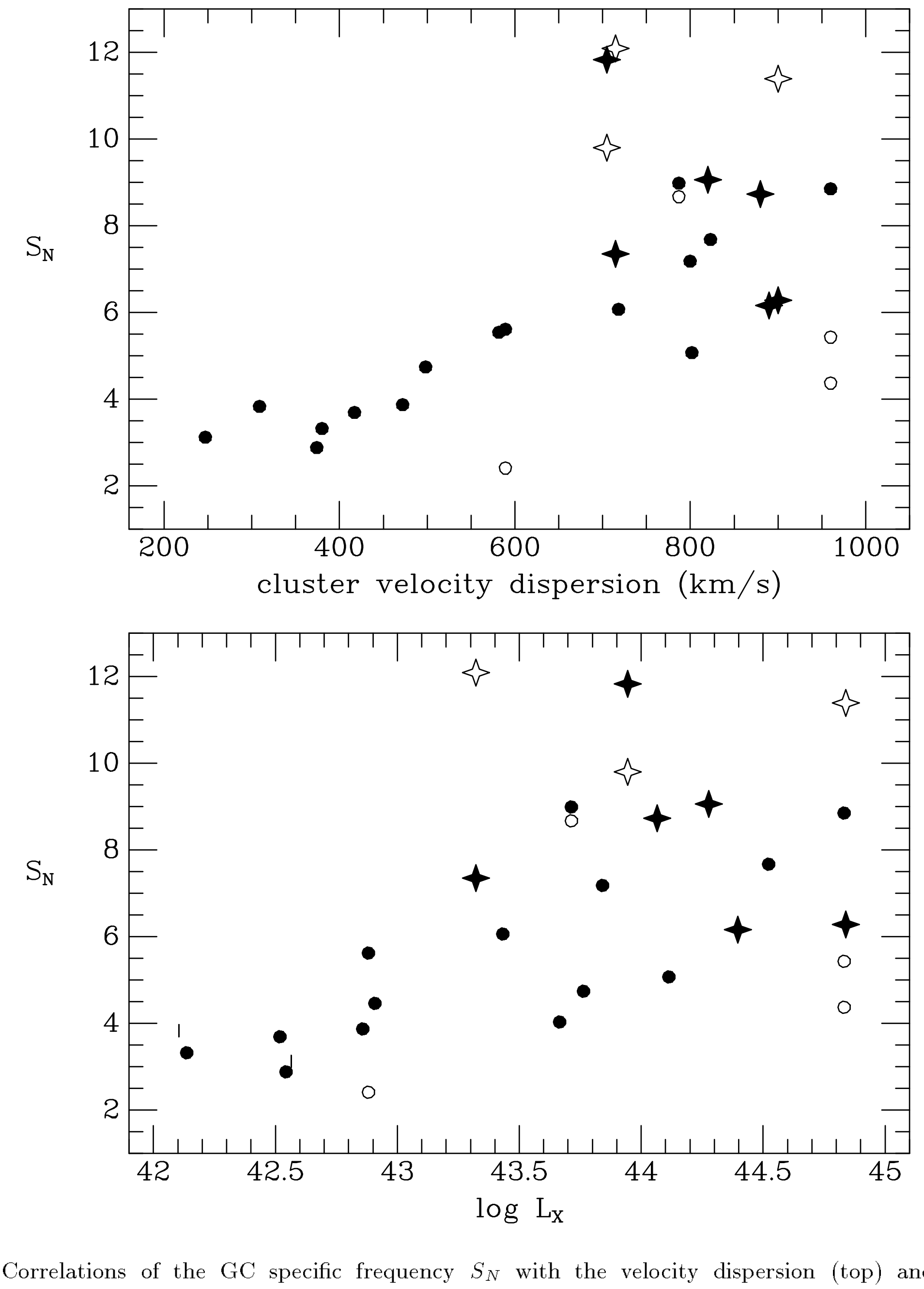

Figure 4: Correlations of the GC specific frequency S_N with the velocity dispersion (top) and the X-ray luminosity (bottom) of the host galaxy cluster. Filled and open circles respectively represent central and non-central ("secondary") bright cluster galaxies from the complete $cz < 10,000$ km s^{-1} sample studied by Blakeslee et al. (1997). Filled four-pointed stars show results for the cD galaxies in the Blakeslee (1999) sample, and open stars are for several fainter ellipticals in those same central fields. (Short vertical lines in the lower panel represent clusters in the former study with only upper limits on X-ray luminosity.) Thus, the filled symbols are all dominant central galaxies. However, open circles are high-luminosity non-central galaxies, while open stars are low-luminosity galaxies near the cD. If the number of GCs depends more on central location than on luminosity, then the former galaxies should have lower S_N values than the latter galaxies, which in turn should have S_N values similar to the central dominant galaxies, consistent with the results shown in these figures.

the slope of the dark matter profile near the centers of galaxy clusters. This will provide a useful comparison for high-resolution N-body simulations (e.g., Moore et al. 1998).

At larger distances where GCs become too faint for spectroscopic measurements, observations of GC populations around cD galaxies can give a reasonable indication of the cluster core mass. The reason for the elevated specific frequencies of the central galaxies is most likely that their gas was removed and their star formation halted sometime after the formation of the GCs. In this case, it should be possible to observe S_N evolution in clusters of different evolutionary states, but the available data are inconclusive. As always, future observations of GC systems from the ground and with *HST* will be helpful in resolving the many remaining questions.

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