*Near-Field Cosmology with Dwarf Elliptical Galaxies*
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# An HST/ACS survey of early-type galaxies in the Virgo cluster

**Patrick Côté**

Herzberg Institute of Astrophysics, National Research Council of Canada,
5071 W. Saanich Road, Victoria, BC, V9E 2E7, CANADA
email: Patrick.Cote@nrc-cnrc.gc.ca

**Abstract.** One hundred early-type members of the Virgo Cluster have been observed with the *Hubble Space Telescope* (*HST*) as part of the ACS Virgo Cluster Survey. The survey and its extensions consists of F475W and F850LP imaging from the *Advanced Camera for Surveys* (ACS), supplemented by additional imaging and spectroscopy from WFPC2/*HST*, *Chandra*, *Spitzer*, Keck, KPNO, and CTIO. In this article, I report briefly on four scientific highlights from the program: (1) the discovery of a population of probable ultra-compact dwarf galaxies; (2) an improved measurement of the frequency of compact stellar nuclei in early-type galaxies; (3) a precise new measurement of Virgo's line-of-sight depth; and (4) new insights into the chemical evolution of galaxies from the color distributions of their globular cluster systems.

**Keywords.** galaxies: clusters: individual (Virgo)–galaxies: elliptical and lenticular-galaxies: dwarf–galaxies: nuclei–galaxies: structure–galaxies: star clusters

## 1. Introduction

The Virgo Cluster marks the center of the Local Supercluster (de Vaucouleurs 1956) and, as the attendees of this meeting are well aware, contains by far the largest collection of dwarf galaxies in the local universe. As a result, Virgo's rich population of dwarf galaxies has long played a pivatol role in our understanding of the structure and stellar content of low-mass galaxies, and how they form and evolve in dense cluster environments (e.g., Reaves *et al.* 1983; Caldwell 1983; Binggeli, Sandage & Tammann 1985; Binggeli, Tammann & Sandage 1987; Bothun *et al.* 1985; Ichikawa, Wakamatsu & Okamura 1986; Binggeli & Cameron 1991, 1993; Durrell 1997; Lotz, Miller & Ferguson 2004). Such galaxies have taken on a renewed importance in recent years, following the recognition that their observed numbers, spatial distribution and stellar content impose tight constraints on hierarchical models of structure formation (e.g., Moore *et al.* 1999; Klypin *et al.* 1999; Mayer *et al.* 2002).

With the installation of the *Advanced Camera for Surveys* (ACS) on the *Hubble Space Telescope* (*HST*) in 2002, the already outstanding imaging capabilities of this observing facility improved dramatically (i.e., by roughly a factor of ten in "discovery efficiency"; Ford *et al.* 1998). In an effort to capitalize on this tremendous gain in efficiency, my colleagues and I initiated the *ACS Virgo Cluster Survey* — an ambitious program to image, in two bandpasses (F475W and F850LP), 100 early-type members of the Virgo Cluster. Since then, a number of additional observing programs focussing on the survey galaxies have been undertaken, including imaging and spectroscopy from WFPC2/*HST*, *Chandra*, *Spitzer*, Keck, KPNO, and CTIO. Full details on the observational strategy and science drivers for the original program are given in Côté *et al.* (2004), while scientific results have been presented in Jordán *et al.* (2004ab), Mei *et al.* (2005ab) and Haşegan *et al.* (2005).



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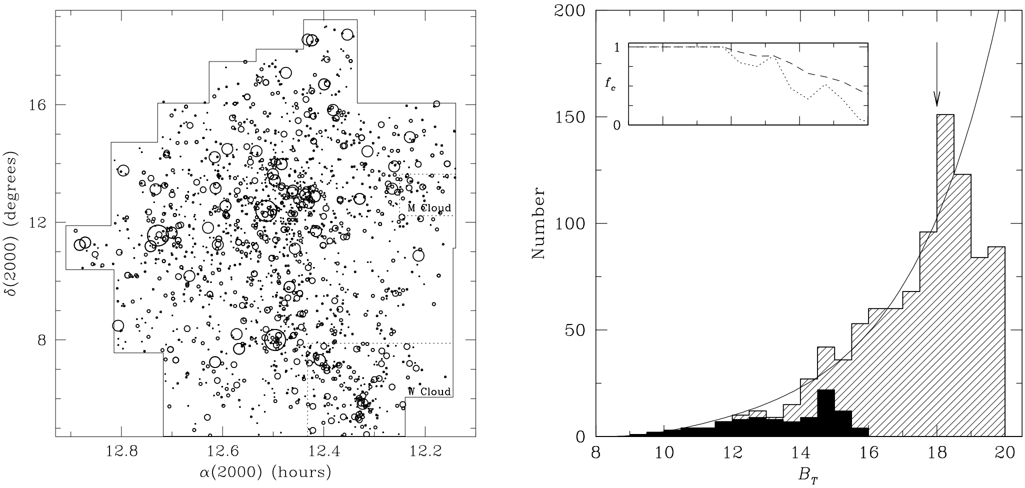


**Figure 1. (Left Panel)** Distribution of Virgo Cluster galaxies on the plane of the sky, adapted from Binggeli *et al.* (1987). This figure contains a total of 1726 galaxies – with no restriction on morphological type – which are classified as members or possible members of Virgo and have declinations $\delta \gtrsim 5°$. Red symbols denote the full sample of 100 early-type galaxies from the ACS Virgo Cluster Survey (Côté *et al.* 2004). The symbol size in all cases is proportional to blue luminosity. **(Right Panel)** Luminosity function of 956 early-type galaxies classified by Binggeli *et al.* (1987) as members of Virgo (upper, hatched histogram). The arrow shows the completeness limit of the Virgo Cluster Catalog, while the solid curve shows the best-fit Schechter function for E+S0+dE+dS0 galaxies from Sandage *et al.* (1985). The filled lower histogram shows the luminosity function of the 100 early-type galaxies from the ACS Virgo Cluster Survey. (Inset panel) Differential (dotted curve) and cumulative (dashed curve) completeness fractions for the ACS Virgo Cluster Survey over the range $9 \leqslant B_T \leqslant 16$. Figures from Côté *et al.* (2004).

The ACS Virgo Cluster Survey was intended to provide as complete a picture as possible of early-type cluster galaxies in the magnitude range $9.3 \lesssim B_T \lesssim 16$ ($-21.7 \lesssim M_B \lesssim -15$). The distribution of our 100 program galaxies on the plane of the sky is shown in the left panel of Figure 1; the right panel of this figure compares the luminosity distribution of our program galaxies with that of the full sample of early-type members of Virgo from the survey of Binggeli *et al.* (1985). Our sample contains roughly half of all early-type members down to $B_T \leqslant 16$ ($M_B \leqslant -15$) and includes a complete sample of early-types brighter than $B_T = 12$ ($M_B = -19$). In terms of Virgo's dwarf population, 35 of the 100 program galaxies are formally classified as dwarfs according to the morphologies presented in Binggeli *et al.* (1985). If one instead adopts a crude luminosity division between dwarfs and giant galaxies of $M_B \approx -17.5$ (Kormendy 1985), then 53 of the 100 galaxies would qualify as dwarfs.

In this article, I shall focus on a handful of recent scientific highlights from the survey, including the detection of a population of "ultra-compact dwarf" galaxies in Virgo (Haşegan *et al.* 2005), a sharp upward revision in the frequency of compact nuclei in early-type galaxies (Côté *et al.* 2005), a new measurement of the line-of-sight depth of the Virgo Cluster (Mei *et al.* 2005c), and a systematic exploration of the dependence of globular cluster colors on host galaxy properties (Peng *et al.* 2005). More details on each of these topics may be found in the cited papers.

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## 2. Ultra-Compact Dwarf Galaxies

The data reduction pipeline for globular clusters in the ACS Virgo Cluster Survey includes object detection, the identification of cluster candidates, and the measurement of their photometric and structural parameters (Jordán *et al.* 2004a). This final step relies on maximum-likelihood fitting of psf-convolved King models to the two-dimensional light distributions of the detected sources (see the appendix in Jordán *et al.* 2005 for details). While the overwhelming majority of the globular clusters in Virgo have half-light radii, $r_h$, resembling those of globular clusters in the Milky Way, a handful of objects in our M87 field were found to be much brighter and larger than typical Galactic globulars (with $r_h \sim 0''.3 \sim 25$ pc, ten times larger than the Galactic average; see the left panel of Figure 2).

In terms of size and luminosity, these objects are intermediate to globular clusters and dwarf galaxies. Indeed, they resemble the so-called ultra-compact dwarf galaxies reported recently in the Fornax Cluster (e.g., Hilker *et al.* 1999; Drinkwater *et al.* 1999). Follow-up echelle (ESI) spectroscopy with the Keck telescope for six of these objects has been used to measure their mass-to-light ratios (Haşegan *et al.* 2005). The results are plotted in the right panel of Figure 2, which compares the measured mass-to-light ratios to those of globular clusters and the predictions of single-burst stellar population synthesis model from Bruzual & Charlot (2003).

There are two important conclusions to be drawn from this figure. First, our small sample appears to be rather heterogeneous, with three, or possibly four, objects having mass-to-lights that are larger than either globular clusters or the model predictions. These objects are prime candidates for ultra-compact dwarf galaxies. The two remaining objects have mass-to-light ratios which are slightly higher than those of most Galactic globular clusters, but the measured values are nevertheless consistent with the theoretical predictions for globular clusters because of their relatively high metallicities. Second, it is clear that extreme caution must be excercised when attempting to distinguish ultra-compact dwarf galaxies from high-luminosity globular clusters. It is *not* possible to do so on the basis of luminosity alone; structural parameters and (especially) mass-to-light ratios are required.

## 3. Compact Nuclei in Early-Type Galaxies

*HST* imaging of spiral galaxies has shown that ≈50–70% of them contain compact stellar nuclei near their photocenters (e.g., Phillips *et al.* 1996; Carollo, Stiavelli & Mack 1999; Böker *et al.* 2004). The origin of these nuclei remains a mystery, with possible formation mechanisms ranging from highly concentrated star formation driven by infall of chemically-enriched gas, to the merger of star clusters driven to the galaxy center by dynamical friction. Discriminating between the various scenarios requires a comparison of the properties of the nuclei across galaxies of differing type and luminosity. Unfortunately, there has been no comparably sensitive search for compact stellar nuclei in the inner regions of early-type galaxies.

Based on the morphological classifications of Binggeli *et al.* (1985, 1987), our sample of 100 early-type galaxies includes 25 nucleated galaxies (24 dE,Ns and one nucleated elliptical). However, this value of $f_n = 25\%$ for the frequency of nuclei in our program galaxies should be considered a firm lower limit on the true frequency. Binggeli *et al.* (1985, 1987) state explicitly that faint nuclei – and those in bright, high-surface brightness galaxies – would have gone undetected in their photographic survey. The left panel of Figure 3 demonstrates the importance of these selection effects by comparing the

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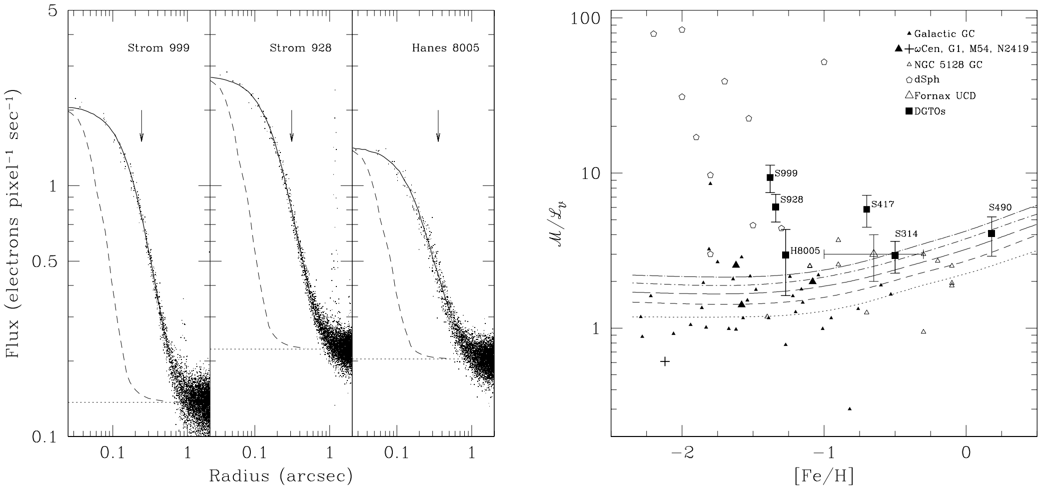


**Figure 2. (Left Panel)** Radial brightness profiles for three ultra-compact dwarf candidates from the ACS Virgo Cluster Survey. In each panel, the adopted background is indicated by the dotted line. The solid curve shows the best-fit, psf-convolved King model. The dashed curve shows the F475W psf, while the arrow indicates the fitted half-light radius. All three objects are found in our ACS images of M87, and were previously classified as M87 globular clusters on the basis of ground-based photometry and spectroscopy (e.g., Côté *et al.* 2001). **(Right Panel)** Mass-to-light ratio versus metallicity for hot stellar systems. Triangles show globular clusters in the Milky Way and NGC5128. The six squares show candidates ultra-compact dwarfs in M87. From bottom to top, the five curves show the theoretical predictions of the population synthesis models of Bruzual & Charlot (2003) for ages of 7, 9, 11, 13 and 15 Gyr. These models assume a Chabrier (2003) initial mass function. Figures from Haşegan *et al.* (2005).

visual appearance of one dwarf galaxy (the brightest non-nucleated dwarf in our sample according to the original ground-based classifications) with its simuated appearance from the ground. It should come as no surprise that *HST* is well suited to the detection of faint, compact nuclei in Virgo Cluster galaxies.

The right panel of Figure 3 compares the luminosity distribution of the complete sample of ACS Virgo Cluster Survey galaxies (upper histogram) with the 25 galaxies classified as nucleated in the Virgo Cluster Catalog (filled histogram). Two additional histograms show the distributions for galaxies which we find to have *unambiguous* nuclei (double-hatched histogram) and those which have *certain or possible* nuclei (hatched histogram). These classifications are based on visual inspections of the *HST* images and modeling of the galaxy surface brightness profiles. Depending on the which sample is considered, our estimate for the frequency of nuclei falls in the range 66–82%, which is comparable to *HST* measurements for late-type systems but much higher than previous estimates for early-type galaxies from photographic surveys. The implications of this finding are discussed at length in Côté *et al.* (2005).

## 4. The Depth of the Virgo Cluster

On the sky, the Virgo Cluster appears complex and irregular, with a diameter of ≈10°. The structure of the cluster along the line of sight is a matter of longstanding debate, with estimates of the back-to-front depth varying wildly. At one extreme, Young & Currie (1995) report a depth of ±6–8 Mpc by employing the shape of the brightness profiles for

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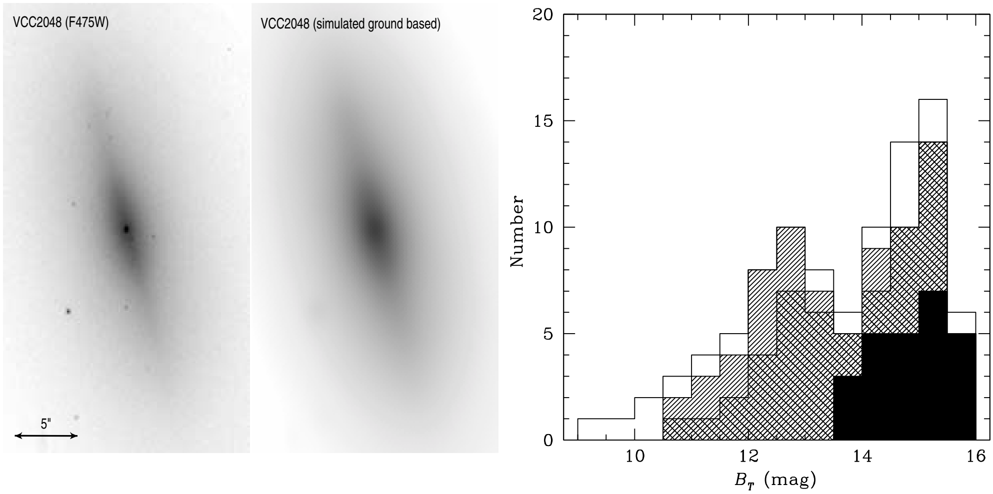


**Figure 3. (Left Panel)** Two views of the inner region of VCC2048, the brightest dwarf galaxy in our sample according to the morphological classifications of Binggeli, Sandage and Tamman (1985). This galaxy is classified as *non-nucleated* in the Virgo Cluster Catalog, with morphological type d:S0(9). On the left, we show the F475W image from our survey; on the right, we show this same image after binning $4 \times 4$ and convolving with a Gaussian of FWMH $= 1''.4$ to simulate its appearance in conditions of moderate ground-based seeing. **(Right Panel)** Luminosity distribution of the 94 program galaxies for which a classification as either nucleated or non-nucleated is possible from our ACS imaging (open histogram). The hatched histogram shows the luminosity distribution for the 62 galaxies which we find to show unambiguous evidence of nucleatation. The double-hatched histogram shows this same sample plus 15 additional galaxies which *may* have central nuclei. The solid histogram shows the 25 galaxies in our survey which were classified as nucleated in the Virgo Cluster Catalog (Binggeli *et al.* 1985). Figures from Côté *et al.* (2005).

dwarf elliptical galaxies as a distance indicator, and a similar extent for spiral galaxies in Virgo has been reported by Yasuda, Fukugita, & Okamura (1997) using the Tully-Fisher relation. Meanwhile, measurements of Virgo's depth from the method of surface brightness fluctuations usually find a much smaller depth of a few Mpc (e.g., Neilsen & Tsvetanov 2000).

The ACS Virgo Cluster Survey was designed to provide accurate distances for our program galaxies through the $z$-band surface brightness fluctuations (see Figure 7 of Côté *et al.* 2004). Details of our implementation of this method are given in Mei *et al.* (2005ab), and in Figure 4 we show our adopted calibration. A thorough analysis of Virgo's three-dimensional structure will be presented in Mei *et al.* (2005c). For the time being, we can use these data to crudely estimate the line-of-sigh depth of Virgo.

The *rms* dispersion in distance modulus of the galaxies shown Figure 4 is 0.12 mag. Based on our simulations, we believe that the average error on these measurements is $\sim$0.03 mag, while the instrinsic stellar population scatter in the $z$-band fluctuation magnitudes is estimated to be $\sim$0.06 mag. Thus, our estimate for the intrinsic *rms* dispersion in the distance moduli is $\approx$0.10 mag. For our assumed distance of 16.5 Mpc (Tonry *et al.* 2001), this translates into a 1-$\sigma$ distance dispersion of 0.8 Mpc, or a 2-$\sigma$ line-of-sight *depth* of $\approx$3 Mpc. This value is consistent with previous surface brightness fluctuation measurements based on smaller samples (e.g., Neilsen & Tsvetanov 2000;

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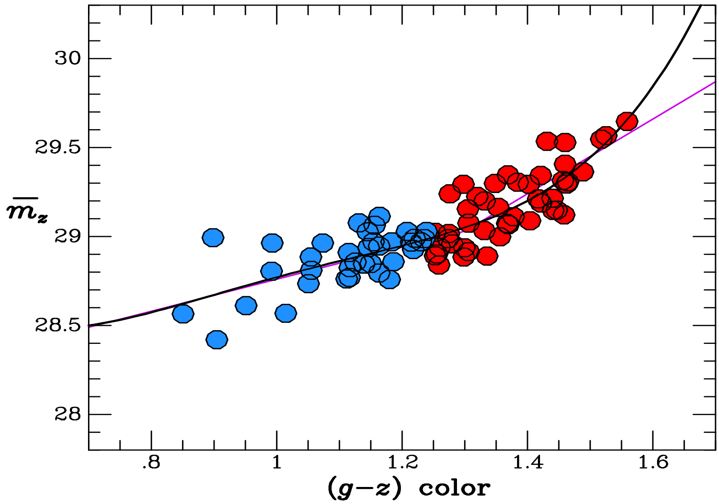


**Figure 4.** Calibration of the $z$-band surface brightness fluctuation method for the ACS Virgo Cluster Survey. A total of 82 galaxies are shown in this figure. The broken linear fit is the calibration from Mei *et al.* (2005b), while the continuous curve is a fourth-order polynomial fit. Different symbols are used to denote the galaxies on either side of the dwarf-giant transition region at $(g - z) \approx 1.25$.

West & Blakeslee 2000; Jerjen, Binggeli & Barazza 2004) and effectively rules out the very extended, cigar-like distributions found by some other researchers.

## 5. Globular Cluster Color Distributions

During the past decade, *HST* has revolutionized our understanding of extragalactic globular cluster systems. Perhaps the single most remarkable development in this field has been the realization that the color distributions of globular cluster belonging to luminous early-type galaxies are usually bimodal in nature (e.g., Gebhardt & Kissler-Patig 1999). The importance of the measured color distributions can scarcely by overestimated as they provide direct, quantitative insights into the processes of mergers and accretions which have shaped their host galaxies (Côté, West & Marzke 2002; Beasley *et al.* 2002; Li, Mac Low & Klessen 2004).

The ACS Virgo Cluster Survey offers a unique opportunity to measure globular cluster color distributions with unprecedented accuracy — given the depth and uniformity of the survey, and the fact that the $(g - z)$ index has twice the metallicity sensitivity of the $(V - I)$ index — and at, the same time, to trace the systematic evolution of the color distributions over a factor of ∼450 in host galaxy luminosity. Figure 5 shows the behavior of globular cluster color distributions from the survey (Peng *et al.* 2005). Mean color histogram are shown in bins of host galaxy color; by virtue of the galaxy color-magnitude relation, the panels also reveal the evolution of the color distributions as one moves from bright (red) giants to faint (blue) dwarfs (the upper left and lower right panels, respectively).

The evolution is striking, with two particularly noteworthy features. First, the fractional contribution of the red sub-population shows a dramatic variation with galaxy color and luminosity. Among the giant galaxies, red clusters account for ∼60% of the total cluster population; at the faint end of the sample, just ∼15% of the clusters are associated with the red component. Second, the peak of the red sub-population shows

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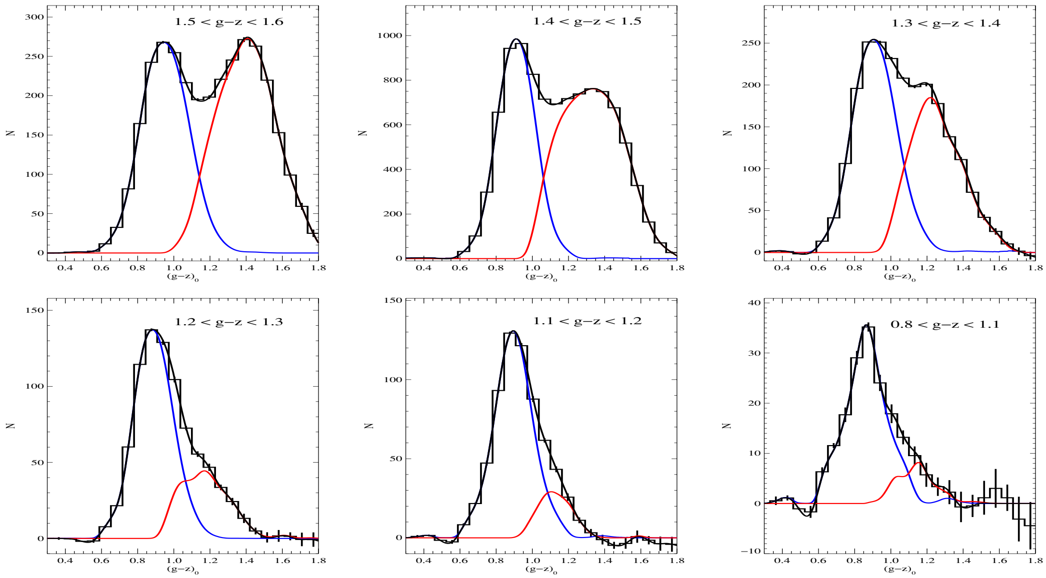


**Figure 5.** Color histograms and two-gaussian fits to globular clusters from the ACS Virgo Cluster Survey binned by host galaxy color. Note the sharp decrease in the relative number of red clusters — and the blueward shift in the mean color of this population — as one moves from giant to dwarf galaxies. Figure from Peng *et al.* (2005).

an unmistakable migration towards bluer colors as the luminosity of the host galaxy decreases. Peng *et al.* (2005) examines these findings in the context of formation scenarios for galaxies and their globular cluster systems.

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## References

Beasley, M.A., Baugh, C.M., Forbes, D.A., Sharples, R.M. & Frenk, C S. 2002, *MNRAS* 333, 383

Binggeli, B. & Cameron, L.M. 1991, *A&A* 252, 27

Binggeli, B. & Cameron, L.M. 1993, *A&AS* 98, 297

Binggeli, B., Sandage, A. & Tammann, G.A. 1985, *AJ* 90, 1681

Binggeli, B., Tammann, G.A. & Sandage, A. 1987, *AJ* 94, 251

Böker, T., Sarzi, M., McLaughlin, D.E., van der Marel, R.P., Rix, H.-W., Ho, L.C. & Shields, J.C. 2004, *AJ* 127, 105

Bruzual, G. & Charlot, S. 2003, *MNRAS* 344, 1000

Caldwell, N. 1983, *AJ* 88, 804

Carollo, C.M., Stiavelli, M. & Mack, J. 1998, *AJ* 116, 68

Chabrier, G. 2003, *PASP* 115, 763

https://doi.org/10.1017/S1743921305003911 Published online by Cambridge University Press

Côté, P., West, M.J., & Marzke, R.O. *et al.* 2002, *ApJ* 567, 853
Côté, P., Blakeslee, J.P., Ferrarese, L., Jordán, A., Mei, S., Merritt, D., Milosavljević, M., Peng, E., Tonry, J.L. & West, M.J. 2004, *ApJS* 153, 223
Côté, P. *et al.* 2005, in preparation
de Vaucouleurs, G. 1956, *Vistas Astron*, 2, 1584
Drinkwater, M.J., Phillipps, S., Gregg, M.D., Parker, Q.A., Smith, R.M., Davies, J.I., Jones, J.B. & Sadler, E.M. 1999, *ApJ* 511, L97
Durrell, P.R. 1997, *AJ* 113, 531
Ford, H.C., *et al.* 1998, *Proc. SPIE* 3356, 234
Gebhardt, K. & Kissler-Patig, M. 1999, *AJ* 118, 1526
Haşegan, M., Jordán, A., Côté, P., Djorgovski, S.G., McLaughlin, D.E., Blakeslee, J.P., Mei, S., West, M.J., Peng, E.W., Ferrarese, L., Milosavljević, M., Tonry, J.L. & Merritt, D. 2005, *ApJ* 627, 203
Hilker, M., Infante, L., Vieira, G., Kissler-Patig, M. & Richtler, T. 1999, *A&AS* 134, 75
Ichikawa, S.-I., Wakamatsu, K.-I. & Okamura, S. 1986, *ApJS* 60, 475
Jerjen, H., Binggeli, B. & Barazza F.D. 2004, *AJ* 127, 771
Jordán, A., Blakeslee, J.P., Peng, E., Côté, P., Ferrarese, L., Mei, S., Merritt, D., Milosavljević, M., Tonry, J.L. & West, M.J. 2004a, *ApJS* 154, 509
Jordán, A., Côté, P., Ferrarese, L., Blakeslee, J.P., Mei, S., Merritt, D., Milosavljević, M., Peng, E., Tonry, J.L. & West, M.J. 2004b, *ApJ* 613, 279
Jordán *et al.* 2005, *ApJ* submitted
Klypin, A., Kravtsov, A.V., Valenzuela, O. & Prada, F. 1999, *ApJ* 522, 82
Kormendy, J. 1985, *ApJ* 295, 73
Li, Y., Mac Low, M.-M. & Klessen, R.S. 2004, *ApJ* 614, 29
Lotz, J.M., Miller, B.W., & Ferguson, H.C. 2004, *ApJ* 613, 262
Mayer, L. Moore, B., Quinn, T., Governato, F. & Stadel, J. 2002, *MNRAS* 336, 199
Mei, S., Blakeslee, J.P., Tonry, J.L., Jordán, A., Peng, E.W., Côté, P., Ferrarese, L., Merritt, D., Milosavljevic, M. & West, M.J. 2005a, *ApJS* 156, 113
Mei, S., Blakeslee, J.P., Tonry, J.L., Jordán, A., Peng, E.W., Côté, P., Ferrarese, L., Merritt, D., Milosavljevic, M. & West, M.J. 2005b, *ApJ* 625, 121
Mei, S. *et al.* 2005c, in preparation
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J. & Tozzi, P. 1999, *ApJ* 524, L19
Neilsen, E.H. & Tsvetanov, Z.I. 2000, *ApJ* 536, 255
Peng, E.W. *et al.* 2005, *ApJ* submitted
Phillips, A.C., Illingworth, G.D., MacKenty, J.W. & Franx, M. 1996, *AJ* 111, 1566
Reaves, G. 1983, *ApJS* 53, 375
Sandage, A., Binggeli, B. & Tammann, G.A. 1985, *AJ* 90, 1759
Tonry, J.L., Dressler, A., Blakeslee, J.P., Ajhar, E.A., Fletcher, A.B., Luppino, G.A., Metzger, M.R. & Moore, C.B. 2001, *ApJ* 546, 681
Yasuda, N., Fukugita, M. & Okamura, S. 1997, *ApJS* 108, 417
Young, C.K. & Currie, M.J. 1995, *MNRAS* 273, 1141
West, M.J. & Blakeslee, J.P. 2000, *ApJ* 543, 27

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