The ACS Intermediate Redshift Cluster Survey: Cluster Evolution at Redshift Around Unity

S. Mei, J.P. Blakeslee, R. Demarco, H. Ford, N. Homeier, and M. Postman
Dept. of Physics &Astronomy, Johns Hopkins University, Baltimore, MD 21218
M. Franx
Leiden Observatory, Postbus 9513, 2300 RA Leiden, Netherlands.
B.P. Holden and G.D. Illingworth
Lick Observatory, University of California, Santa Cruz, CA 95064
P. Rosati
European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
and the ACS IDT team

The ACS Intermediate Redshift Cluster Survey is an ongoing GTO project to study the properties and evolution of clusters and their member galaxies near redshift unity with the Wide Field Channel of the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope. The survey includes eight X-ray and optically selected galaxy clusters in the redshift range z=0.8 to z=1.3. Our goals include constraining the formation ages and the star formation histories of early-type galaxies, and comparing the fundamental properties of clusters of galaxies from z≈1 to the present (Ford et al. 2004). Here we present our observations from this survey and summarize some recent results on the color-magnitude and morphology-density relations as well as the star formation activity of cluster galaxies.

1. Introduction

The Advanced Camera for Surveys (ACS; Ford et al. 2002), by virtue of its high resolution and sensitivity, permits us to study galaxy clusters in great detail up to redshifts of unity and beyond. At these redshifts, galaxy clusters are still assembling and galaxies are evolving towards the populations that we observe today.

Our ACS Intermediate Redshift Cluster Survey includes eight clusters, X–ray, optical and near–infrared (near–IR) selected, in the redshift range $0.8 < z < 1.3$ (Ford et al. 2004). Recent results from the ACS Intermediate Redshift Cluster Survey (Blakeslee et al. 2003a; Lidman et al. 2004; Demarco et al. 2005; Goto et al. 2005; Holden et al. 2005a; Holden et al. 2005b; Homeier et al. 2005; Postman et al. 2005) have shown that galaxy clusters at redshift around unity show many similarities with local clusters, in terms of galaxy populations and their spatial distribution, but also significant differences in galaxy morphology, ellipticity, and mass–luminosity ratios. The strongest evolution observed in the early–type population is a deficit of a S0 population in this sample when compared to lower redshift samples (Postman et al. 2005). This would give evidence that the formation of the S0 population is still under way in clusters at redshift unity.

One of the most striking similarities is that the tight relation between galaxy colors and luminosities that applies to local early–type galaxies (the color–magnitude relation; CMR) is already in place at redshifts as high as $z \sim 1.3$ (e.g. Stanford et al. 1997; Mullis et al. 2005). The CMR in local samples of galaxy clusters presents universal properties, in terms of scatter and zero point (Bower et al. 1992; van Dokkum et al. 1998, Hogg et al. 2004; López–Cruz et al. 2004; Bell et al. 2004; Bernardi et al. 2005; McIntosh et al. 2005) that evolve back in time in agreement with passively evolving models (Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998; van Dokkum et al. 2000, 2001; Blakeslee et al. 2003; Holden et al. 2004; De Lucia et al. 2004).

Table I ACS Intermediate Redshif Cluster Survey sample

Cluster	z	σ_v	L_X	
		km/s	10^{44} erg/s	ACS Filters
MS1054+03	0.83	1112	23.3	V,i,z
RXJ0152+1357	0.84	1250	7.8	r,i,z
CL 1604+4304	0.90	989	2.0	V,I
CL 1604+4321	0.92	649	< 1.2	V,I
RXJ0910+5422	1.10		1.5	i,z
RXJ1252-2927	1.24	760	4.0	i,z
RXJ0848+4452	1.26		1.0	i,z
RXJ0848+4453	1.27	640	1.5	i,z

In this paper, we summarize some recent results on the color-magnitude, morphology-density, and star formation activity.

1.1. The ACS Intermediate Cluster Survey

The ACS Intermediate Redshift Cluster Survey sample (Ford et al. 2004) and cluster properties are shown in Table I. Five of the clusters were identified

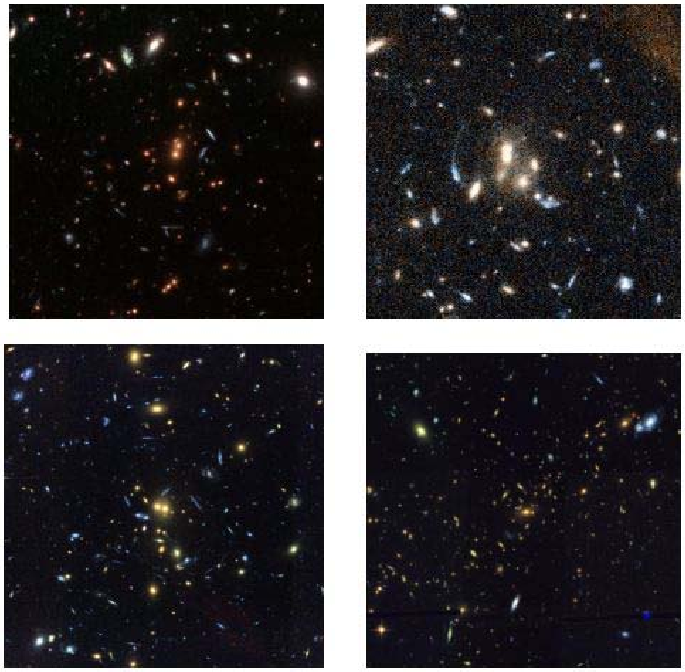

Figure 1: On the top, the central regions of RXJ1252-2927 (left) and RXJ0848+4452 (right). On the bottom, RXJ0152+1357 (left) and MS1054+03 (right).

from the ROSAT Deep Cluster Survey (Rosati et al. 1998), one from the Einstein Extended Medium Sensitivity Survey (Gioia & Luppino 1994; MS1054) and two from a Palomar deep near–infrared photographic survey (CL1604+4304 & CL1604+4321; Gunn et al. 1986). Most of the cluster have extensive spectroscopy.

In Fig 1 we show the ACS images for RXJ1252.9-292, the center of RXJ0848+4452, RXJ0152+1357 and MS1054+03. The ACS image quality is remarkable.

1.2. Color–magnitude relation

ACS enables accurate measurement of the scatter around the color–magnitude relation (CMR), with enough precision to seriously constrain galaxy formation age, which is impossible to obtain from ground–based data (see for example Holden et al. 2004). The measurement of the CMR scatter of the first cluster in our ACS cluster survey, RXJ1252.9-292, permitted us to derive the mean luminosity weighted age of the last epoch of star formation in the red early–type populations, by using a simple stellar population model (Blakeslee et al. 2003).

To construct the CMR, early–type galaxies with $0.8 < (i_{775} - z_{850}) < 1.2$ mag were selected from the Postman et al. (2005) morphological classification (see section below), down to $z_{850} = 24$ mag. Final colors were measured within galaxy effective radii (R_e), to avoid biases due to galaxy internal gradients. R_e values were derived with the program GALFIT (Peng et al. 2002), constraining the *Sersic* index $n \leq 4$. To remove blurring effects (the PSF is 10% broader in the z_{850} band) each galaxy image in both i_{775} and z_{850} was deconvolved using the CLEAN algorithm (Högbom et al. 1974). The $(i_{775} - z_{850})$ colors were measured on the deconvolved images within a circular aperture equal to R_e.

The early-type population in RXJ1252.9-292 shows a small intrinsic scatter in the CMR, with an intrinsic scatter in observed $(i_{775} - z_{850})$ color of 0.029 ± 0.007 mag based on 52 galaxies or 0.024 ± 0.008 mag for 30 elliptical galaxies (Fig 2). Simulations using the latest stellar population models from Bruzual & Charlot (2003) permit us to derive an age scatter for the elliptical galaxies of about 34%, with a mean age of > 2.6 Gyr (corresponding to $z > 2.7$), and the last star formation occurring at $z > 1.5$. Transforming to rest-frame (U-B) color, Blakeslee et al. (2003) concluded that the slope and scatter in the CMR for morphologically selected early-type galaxies show little or no evidence of evolution out to z≈1.2. Thus, elliptical galaxies were already well established in X-ray-luminous clusters when the universe was a third of its present age.

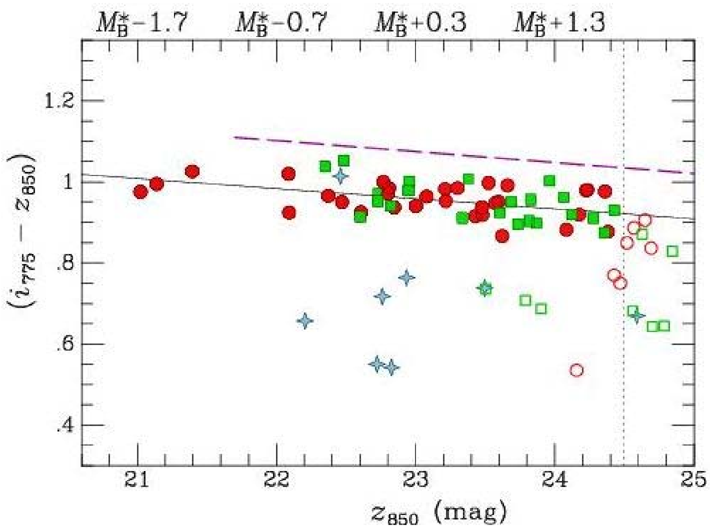

Figure 2: Detailed color-magnitude diagram for RXJ1252.9-292 within 2" (≈ 1 Mpc) from the cluster center. Circles are ellipticals, squares S0's, stars spectroscopically confirmed late-types; filled circles/squares were used for the fit, empty symbols show galaxies that were rejected from the color selection, a three σ clipping and the morphological classification that extends down to z_{850} brighter than 24 mag. The dashed line shows the Coma cluster CMR, transformed to these bandpasses and z=1.24 using Bruzual & Charlot (2003) stellar population models without any evolution correction. The solid line shows the fit to the 15 spectroscopically confirmed ellipticals. Analysis of the color scatter suggests a mean age of 3 Gyr for the early-types (Blakeslee et al. 2003).

Using deep VLT J and K_s images of this same cluster, Lidman et al. (2004) come to a similar conclusion from the analysis of the near–infrared CMR.

Blakeslee et al. (2003) results were extended to the other clusters of the survey: RXJ0152+1357 and MS1054+03 (Blakeslee et al.); RXJ J0910+5422 (Mei et al., submitted to ApJ); RXJ0848+4452 and RXJ0848+4453 (Mei et al., in preparation); CL1604+4304 & CL1604+4321 (Homeier et al., in preparation).

The CMR for the ellipticals in RDCS J0910+5422 is consistent with that found in RDCS 1252.9-292 (Mei et al., submitted to ApJ). However, the CMR for the S0 galaxies in RDCS J0910+5422 is systematically bluer in the observed $(i_{775}-z_{850})$ color by 0.07 ± 0.02 mag, with respect to the elliptical CMR.

1.3. Morphology–density relation

Postman et al. (2005) measured the morphology-density relation (MDR) and morphology-radius relation in seven out of the eight clusters in our ACS Intermediate Cluster Survey (all the them, but RXJ0848+4453). The galaxies were classified according to visual classification using the classical Hubble sequence: ellipticals: E, E/S0; S0s: S0, S0/a; spirals: Sa, Sa/b, Sb, Sb/c, Sc; and irregulars: Irr. The sample was then divided in three broader classes: E, S0s and spirals. Simulations and independent comparisons of our visually derived morphologies indicate that ACS allows one to distinguish between E, S0, and spiral morphologies down to z_{850}=24 mag, corresponding to $L = 0.21L^*$ and $L = 0.3L^*$ at z=0.83 and 1.24, respectively.

The high ACS resolution and sensitivity permits us to distinguish E from S0s, and compare our sample to local samples to study the MDR evolution. In Fig 3 we show our sample as compared to previous MDR studies at redshift around unity, and to local samples at $z < 0.5$. A clear evolution is observed in the fraction of the S0 and spiral populations as a function of density. When compared to local samples a deficit of S0 and an excess of Sp+Irr galaxies is measured in our sample. The evolution in the MDR is confined to densities of ≈ 40 galaxies Mpc^{-2}, in the external regions of the clusters. The elliptical MDR exhibits no significant evolution between z=1 and 0.

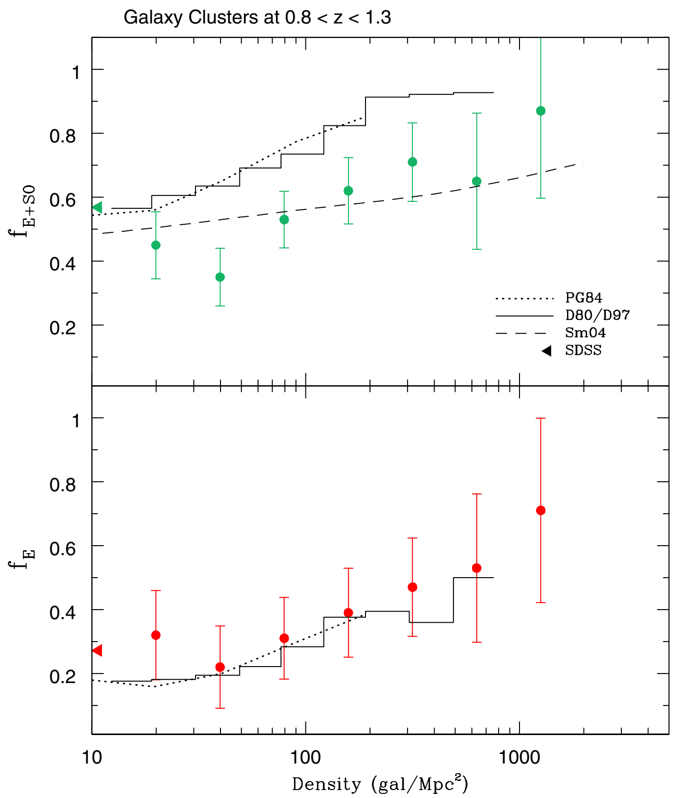

Figure 3: Morphology–density relation from Postman et al. (2005). On the top, we show the total early–type fraction (ellipticals + S0s; top) as a function a galaxy density. Filled circles are data from our ACS Intermediate Redshif Cluster Survey sample at redshift around unity, the dashed line are from Smith et al. (2005) sample at z ≈ 1. The solid and dotted lines are from local samples, from Dressler (1980) and Dressler et al. (1997) and Postman & Geller 1984, respectively. On the bottom, the elliptical fraction is shown, compared to local samples. While the elliptical fraction remains the same in the local and the redshift around unity samples, the total (E+S0s) fraction decreases with redshift. This implies a deficit of S0s at redshifts around unity.

This result suggests that:1) part of the S0 population formed at $z > 1.3$; 2) the formation of the S0 population is still under way in clusters at redshift unity.

1.4. Star formation activity

Demarco et al. (2005) and Homeier et al (2005) have studied star–forming galaxies in RX J0152.7-1357.

Demarco et al. (2005) performed an extensive spectroscopic survey (for a total of more than 200 redshifts) of RX J0152.7-1357 at z=0.837, using FORS1 and FORS2 on the ESO Very Large Telescope (VLT). A number of 102 galaxies were confirmed as cluster members. They combined optical and X–ray Chandra data to study the star–forming galaxy distribution in this cluster.

The distribution of cluster members is irregular, with two main clumps that follow the X-ray cluster emission mapped by Chandra. A third clump of galaxies to the east of the central structure and at the cluster redshift has also been identified.

They also studied the distribution of star-forming galaxies in this cluster and compared this distribution to that of the X-ray emission. A segregation in the star formation activity of the member galaxies is observed (Fig 4). All star forming galaxies are located outside the high-density peaks (traced by the X-ray emission), which are populated only by passive galaxies. A population of red galaxies (belonging to the cluster red sequence) with [OII] λ3727 emission lines is observed in the outskirts of the cluster, some of them showing post-starburst spectral features. Two AGNs, which were previously confused with the diffuse X-ray emission from the intracluster medium in ROSAT and BeppoSAX observations, are found to be cluster members.

Homeier et al. (2005) extended Demarco et al.'s (2005) work to study in more detail the properties of the above star-forming galaxies. From Postman et al.'s (2005) morphological classification they could

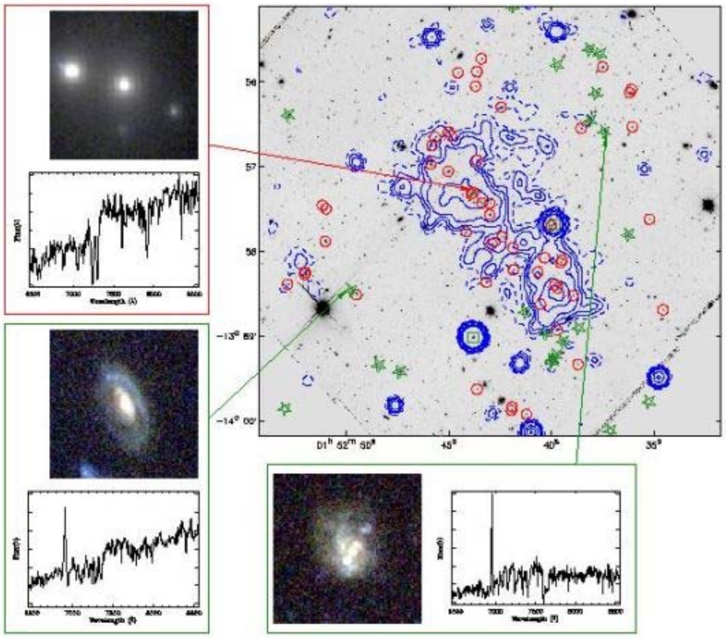

Figure 4: Star-forming (green stars) and passive (red circles) galaxies in RXJ0152+1357, compared to X-ray contours. Star–forming galaxies have been selected from their [OII]λ3737 emission, and are typically late–type galaxies. At z=0.8, cluster galaxies already show strong segregation based on type, with the late–type galaxies distributed in the outskirts of the cluster. Representative spectra are shown (Demarco et al. 2005).

identify 24 star-forming cluster galaxies, which range in morphology from late-type and irregular to compact early-type galaxies. Eight of those 24 are in the red cluster sequence. Among the 24, five are compact early-type galaxies that might be progenitors of dwarf elliptical galaxies. They derived star formation rates (SFR) from [OII] $\lambda\lambda$3727 line fluxes, and compared the global star formation rate of this cluster to other clusters at low and intermediate redshifts. They didn't find evidence of evolution with redshift. A mild correlation between integrated star formation rates and T_X, that is in general correlated to cluster mass, was found (Fig. 5). The hotter clusters have lower integrated star formation rates.

Acknowledgments

ACS was developed under NASA contract NAS 5-32865, and this research has been supported by NASA grant NAG5-7697 and by an equipment grant from Sun Microsystems, Inc. The Space Telescope Science Institute is operated by AURA Inc., under NASA contract NAS5-26555. We are grateful to K. Anderson, J. McCann, S. Busching, A. Framarini, S. Barkhouser, and T. Allen for their invaluable contributions to the ACS project at JHU. We thank W. J. McCann for the use of the FITSCUT routine for our color images. Work supported by Department of Energy contract DE-AC03-76SF00515.

References

Bell, E.F. et al. 2004, ApJ, 608, 883

Bernardi, M., Sheth, R. K., Nichol, R. C., Schneider, D. P., Brinkmann, J. 2005, 129, 61

Blakeslee, J.P., *et al.* 2003, ApJL, 596, 143

Bower, R. G., Lucey, J.R., & Ellis, R.S. 1992, MNRAS, 254, 589

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

De Lucia et al. 2004, ApJL, 610, 77

Demarco, R., et al. 2005, A&A, 431, 381

Dressler, A. 1980, ApJS, 42, 565

Dressler, A. et al. 1997, ApJ, 490, 577

Ellis, R.S., Smail, I., Dressler, A., Couch, W.J., Oemler, A. Jr., Butcher, H., Sharples, R.M. 1997, ApJ, 483, 582

Ford, H. C. et al. 2002, Proc. SPIE, 4854, 81

Ford, H. C. et al. 2004, astro-ph/0408165

Gioia, I. & Luppino, G.A. 1994, ApJS, 94, 583

Goto, T. et al. 2005, ApJ, 621, 188

Gunn, J. E., Hoessel, J. G., Oke, J. B. 1986, ApJ, 306, 30

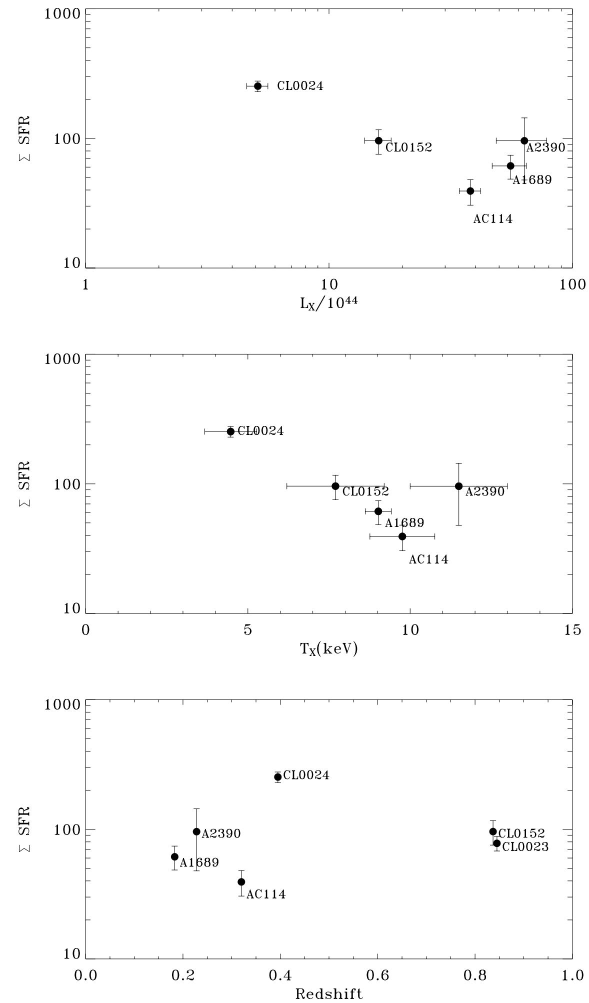

Figure 5: We show integrated SFR as a function of X–ray luminosity (L_x), temperature (T_X) and redshift (Homeier et al. 2005). While we don't observe evolution of SFR with redshift, there is a mild correlation between SFR and cluster L_x and T_X, that might be the evidence of a correlation of SFR with cluster mass.

Högbom, J. A. 1974, A&AS, 15, 417

Hogg, D.W., et al. 2004, ApJL, 601, 29

Holden, B.P., et al., 2004, AJ, 127, 248

Holden, B.P,. et al., 2005a, ApJ, 620, 83

Holden, B.P., et al., 2005b, ApJ, in press

Homeier, N.L., et al. 2005, ApJ, 621, 651

Lidman, C., Rosati, P., Demarco, R., Nonino, M., Mainieri, V., Stanford, S. A., Toft, S. 2004, A&A, 416, 829

López-Cruz, O., Barkhouse, W. A., Yee, H. K. C. 2004, 614, 679

McIntosh, D. H., Zabludoff, A.I., Rix, H.-W., Caldwell, N. 2005, 619, 193

Mullis, C.R., Rosati, P., Lamer, G., Bohringer, H., Schwope, A., Schuecker, P., Fassbender, R. 2005, ApJ, 623, L85

Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H. 2002, AJ, 124, 266

Postman, M. & Geller, M.J. 1984, AJ, 90, 1400

Postman, M., et al. 2005, ApJ, in press

Rosati, Piero; della Ceca, Roberto; Norman, Colin; Giacconi, Riccardo 1998, ApJL, 492, 21

Smith, G.P.; Treu, T., Ellis, R.S., Moran, S.M., Dressler, A. 2005, ApJ, 620, 78

Stanford, S. A., Elston, R., Eisenhardt, P.R., Spinrad, H., Stern, D., Dey, A. 1997, AJ, 114, 223

Stanford, S. A., Eisenhardt, P. R., & Dickinson, M. 1998, ApJ, 492, 461

van Dokkum, P. G., Franx, M., Kelson, D. D., Illingworth, G. D., Fisher, D., & Fabricant, D. 1998, ApJ, 500, 714

van Dokkum, P. G., Franx, M., Fabricant, D., Illingworth, G. D., & Kelson, D. D. 2000, ApJ, 541, 95

van Dokkum, P. G., Stanford, S. A., Holden, B. P., Eisenhardt, P. R., Dickinson, M., & Elston, R. 2001, ApJL, 552, L101