ULTRAVIOLET IMAGING OF THE GALAXY CLUSTER CL 0939 + 4713 (ABELL 851) AT $z = 0.41$

LUCIO M. BUSON,1 FRANCESCO BERTOLA,2 MICHELE CAPPELLARI,3 CESARE CHIOSI,3 ALAN DRESSLER,4 AND AUGUSTUS OEMLER, JR.4

Received 1999 August 16; accepted 1999 October 19

ABSTRACT

The first UV F300W and F218W WFPC2 observations of the rich galaxy cluster CL 0939 + 4713 at $z = 0.41$ are presented and discussed. UV/optical two-color and color-magnitude diagrams of the sources detected in the F300W waveband are constructed. Thanks to preexisting Hubble Space Telescope (HST) optical images of the same field, a morphological classification for the majority of these objects is also provided. Moreover, taking advantage of recent redshift surveys along the CL 0939 + 4713 line of sight, separate diagrams comparing the properties of galaxies belonging to the cluster and to its close projected field are presented. Possible evolutionary effects in the UV from $z \sim 0.4$ to the present time are investigated by comparing the rest-frame (mid-UV/optical) colors of galaxies in CL 0939 + 4713 with balloon-borne data of the Coma Cluster, as well as by resorting to suitable galaxy evolution models. Finally, current attempts to constrain the epoch of the UV-upturn onset in evolved populations by means of HST UV observations are discussed.

Subject headings: galaxies: clusters: individual (Abell 851) — ultraviolet: galaxies

1. INTRODUCTION

Owing to its high richness and distance ($z = 0.41$), CL 0939 + 4713 = Abell 851 turns out to be one of the "most wanted" targets for both morphological and evolutionary studies of galaxy clusters, and thus is presently one of the best-known intermediate-redshift systems. Extensive analyses, including both imaging and spectroscopy, have been carried out from the ground in the optical (Dressler & Gunn 1983, 1992; Fukugita et al. 1995; Belloni et al. 1995; Belloni & Röser 1996; Dressler et al. 1999) and in the IR (Stanford, Eisenhart, & Dickinson 1995, 1998). Besides the above ground-based studies, a large amount of space-borne (Hubble Space Telescope [HST], ROSAT) observing time has been devoted to surveying this cluster (Dressler et al. 1994a, 1994b, 1997; Seitz et al. 1996; Oemler, Dressler, & Butcher 1997; Smail et al. 1997; Andreon, Davoust, & Heim 1997; Schindler & Wambsganss 1996; Schindler et al. 1998).

An important outcome of such (mainly optical) observational efforts is the identification in CL 0939 + 4713 (as well as in the cores of other rich clusters of comparable redshift) of a larger fraction of star-forming galaxies. Such a phenomenon, commonly referred to as the Butcher-Oemler effect (Butcher & Oemler 1978, 1984), is related, in turn, to an excess of late-type spiral, irregular, and merger galaxies, when compared with the nearby galaxy cluster population (e.g., Couch et al. 1994, 1998; Oemler et al. 1997). Analogously, a remarkably higher proportion of the post-star-forming $a + k$ and/or $k + a$ galaxies (previously termed, a bit improperly, E+A galaxies) can be recognized in these intermediate-redshift clusters (Dressler et al. 1999; Poggianti et al. 1999). However, also notable is the presence of a well-developed population of "old" stellar systems, as a substantial fraction of the luminous elliptical galaxies that dominate clusters today seem to be well in place by $z \sim 0.4$.

The unique HST imaging capabilities at ultraviolet wavelengths allow us now to complement the above observations by exploring for the first time the rest-frame, far-, and mid-UV portion of galaxy spectral energy distributions (SEDs) in this rich cluster. The importance of such data can be appreciated, taking into account that mid-UV colors provide tighter constraints to the evolution in time and composition of aging stellar populations than optical-band indices do (cf. Dorman & O'Connell 1997). Moreover, the far-UV region (and, at a lower level, the mid-UV itself) represents direct probes of star formation activity and, through the UV-upturn phenomenon, an additional clue to the composition and age of old populations. The relative intensity of the far-UV flux changes rapidly both for young and old stellar systems indeed, according to either the fast evolution of recently formed UV bright stars or the sudden onset of hot evolved components like those observed in present-day stellar populations of elliptical galaxies.

The very limited access to the UV imaging in the past years heavily hampered these kinds of studies, however. The very few papers available in the literature make use of the data sets provided by the Focal Corrector Anastigmat (FOCA) balloon-borne telescope (Donas, Milliard, & Laget 1995; Donas et al. 1997) and the Ultraviolet Imaging Telescope (UIT) during the Astro-1 and Astro-2 missions on board the space shuttle Endeavour (Cornett et al. 1998). These analyses could not be extended to clusters farther than $z = 0.23$, while the approach recently adopted by Brown et al. (1998) to get deep HST data of the elliptical galaxies in the cluster Abell 370 at $z = 0.375$ is, in turn, hampered by the small size of the Faint Object Camera (FOC) field.

2. OBSERVATIONS AND REDUCTIONS

Ultraviolet images of CL 0939 + 4713 were obtained with the WFPC2 on 1996 January 14–15 (Program ID: 5919). A total of five orbits (2800 s exposure time each) were spent through the near-UV filter F300W (recording the cluster's
rest-frame mid-UV with bandwidth $\Delta \lambda \sim 520 \, \text{Å}$ and central wavelength $\lambda_c \sim 2100 \, \text{Å}$), while 10 additional orbits (again, 2800 s exposure time) were devoted to observations through the less sensitive filter F218W ($\lambda_c \sim 1550 \, \text{Å}$ and $\Delta \lambda \sim 280 \, \text{Å}$ at $z = 0.41$). The adopted WFPC2 field was approximately the same as that chosen for the preexisting optical ($\lambda_c \sim 4870 \, \text{Å}$ and $\Delta \lambda \sim 980 \, \text{Å}$ at cluster distance) F702W images (cf. Dressler et al. 1994b). Our UV images and newly in-flight-calibrated, dearchived optical frames were separately aligned, co-added, and properly cleaned from cosmic-ray signatures. After separately subtracting a constant sky level to each WFPC2 chip (this is made possible also for F702W frames by the higher quality flat-fielding of the data provided by the current pipeline), we performed aperture photometry on the F300W, F218W, and F702W final images. Standard HST magnitudes (STMAG) $m_{300}$ and $m_{702}$ of each obvious source identified in our UV F300W image have been derived, together with $m_{218}$ magnitudes for the two sources identifiable at shorter wavelengths (the flux, within the adopted aperture of 0.6 in radius, is at least 5 $\sigma$ above the noise for all chosen sources). Such an aperture gives the lowest scatter in our derived magnitudes and represents a good compromise between the need of picking up as much signal as possible and avoiding the danger of including more than one object. All UV/optical colors used later in our color-magnitude diagrams (CMDs) refer to the above aperture.

3. RESULTS

For each object detected in the near-UV final image F300W (60 out of the 181 classified in the optical by Dressler et al. 1994b), we provide in Table 1 our measured UV STMAG $m_{300}$, together with the UV/optical color $(m_{300} - m_{702})$. Analogously, for the two F218W-detected galaxies, our derived STMAG $m_{218}$, together with both $(m_{218} - m_{300})$ and $(m_{218} - m_{702})$ colors, is given in Table 2.

Near-UV and optical WFPC2 images are shown in Figures 1 and 2, respectively. The smaller PC1 field has been excluded from our analysis because of the lower signal-to-noise ratio it provides. Observed bright objects in the rest-frame mid-UV (F300W; $\lambda \sim 2100 \, \text{Å}$) are typically spiral galaxies (often with the majority of the UV flux coming from ultraluminous sites of star formation along spiral arms) as well as a few irregular and/or merging galaxies.

Fig. 1.—Five-orbit, co-added near-UV WFPC2 frame of CL 0939+4713 (imaged through the F300W filter). A logarithmic display scale has been adopted. Detected galaxies are marked with a circle and the sequence number adopted in Tables 1 and 2. Note that galaxies identified as sources 32 and 60 are the only objects detected also in mid-UV (F218W) frames. The PC1 field has been excluded from our analysis because of its higher noise.
TABLE 1

| ID   | S97 Number | X    | Y    | m300  | m300−m702 | T Type |
|------|------------|------|------|-------|-----------|--------|
| 1    | 125        | 1256 | 326  | 21.53 | −0.81     | −99    |
| 2    | 660        | 1427 | 1005 | 23.76 | −0.99     | −99    |
| 3    | 301        | 221  | 538  | 23.33 | −1.15     | −99    |
| 4    | 706        | 940  | 1118 | 23.59 | −2.01     | −99    |
| 5    | 892        | 856  | 1505 | 23.63 | −1.18     | −99    |
| 6    | 768        | 1356 | 1265 | 24.11 | −1.78     | −99    |
| 7    | 805        | 1418 | 1356 | 23.78 | −1.77     | −99    |
| 8    | 457        | 156  | 740  | 24.03 | −1.40     | −99    |
| 9    | 64         | 1225 | 256  | 24.61 | −0.38     | −99    |
| 10   | 873        | 1143 | 1463 | 23.85 | −0.71     | −99    |
| 11   | 72         | 969  | 271  | 23.34 | −1.39     | −99    |
| 12   | 866        | 1159 | 1453 | 24.02 | −0.91     | −99    |
| 13   | 674        | 1155 | 1027 | 22.97 | −1.35     | −99    |
| 14   | 136        | 1238 | 341  | 23.78 | −0.95     | −99    |
| 15   | 178        | 1025 | 405  | 23.23 | −0.21     | −99    |
| 16   | 760        | 1048 | 1248 | 24.07 | −0.66     | −99    |
| 17   | 399        | 285  | 635  | 23.92 | −3.15     | −5     |
| 18   | 752        | 1001 | 1230 | 22.60 | −10.6     | −2     |
| 19   | 207        | 871  | 238  | 22.60 | −0.60     | −99    |
| 20   | 738        | 1444 | 1211 | 22.92 | −0.40     | −1     |
| 21   | 427        | 152  | 670  | 23.88 | −3.73     | −5     |
| 22   | 3017       | 44   | 411  | 23.53 | 0.01      | 1      |
| 23   | 456        | 117  | 736  | 23.51 | −0.07     | 2      |
| 24   | 735        | 984  | 1165 | 23.58 | −0.26     | 3      |
| 25   | 43         | 667  | 242  | 23.37 | 0.81      | 4      |
| 26   | 215        | 634  | 430  | 23.29 | 1.26      | 4      |
| 27   | 369        | 830  | 605  | 21.79 | −0.34     | 4      |
| 28   | 763        | 1425 | 1245 | 23.09 | 0.19      | 4      |
| 29   | 497        | 139  | 768  | 20.66 | −1.04     | 4      |
| 30   | 258        | 845  | 484  | 21.52 | 0.05      | 4      |
| 31   | 3006       | 77   | 389  | 23.29 | 0.15      | 5      |
| 32   | 824        | 940  | 1376 | 23.58 | 0.51      | 5      |
| 33   | 422        | 1341 | 681  | 21.91 | −0.30     | 5      |
| 34   | 788        | 1420 | 1315 | 23.16 | −0.79     | 5      |
| 35   | 445        | 1218 | 271  | 23.15 | −0.65     | 5      |
| 36   | 321        | 1089 | 553  | 23.30 | −0.82     | 6      |
| 37   | 224        | 56   | 132  | 22.36 | −0.82     | 6      |
| 38   | 601        | 1287 | 905  | 21.65 | −1.23     | 6      |
| 39   | 261        | 331  | 495  | 22.75 | −0.24     | 6      |
| 40   | 540        | 1150 | 812  | 23.28 | 0.82      | 6      |
| 41   | 84         | 928  | 285  | 23.24 | −0.58     | 6      |
| 42   | 123        | 318  | 293  | 23.87 | 1.17      | 6      |
| 43   | 232        | 760  | 462  | 23.07 | −0.68     | 6      |
| 44   | 806        | 904  | 1337 | 23.84 | −0.48     | 6      |
| 45   | 742        | 1286 | 1208 | 23.86 | 1.24      | 7      |
| 46   | 809        | 1048 | 1348 | 23.18 | −0.74     | 7      |
| 47   | 736        | 1028 | 1199 | 22.91 | −0.29     | 7      |
| 48   | 339        | 937  | 579  | 23.05 | −0.47     | 7      |
| 49   | 489        | 767  | 766  | 22.61 | 0.33      | 7      |
| 50   | 851        | 1117 | 1427 | 23.19 | −0.74     | 7      |
| 51   | 122        | 246  | 308  | 21.86 | 0.30      | 7      |
| 52   | 36         | 300  | 229  | 21.69 | 0.26      | 7      |
| 53   | 342        | 666  | 588  | 23.49 | −0.82     | 10     |
| 54   | 750        | 1125 | 1219 | 22.91 | −1.29     | 10     |
| 55   | 829        | 1122 | 1394 | 23.40 | −0.60     | 10     |
| 56   | 191        | 133  | 422  | 23.29 | −0.43     | 10     |
| 57   | 230        | 734  | 458  | 20.44 | −1.18     | 10     |

Note.—Col. (1): Object identifier; col. (2): cross-identification of objects against the catalog in Smail et al. 1997; col. (3): X centroid on the mosaicked F300W frame in pixels; col. (4): Y centroid on the mosaicked F300W frame in pixels; col. (5): I 2 diameter aperture magnitude (STMAG) measured in the F300W waveband; col. (6): color in a 1 2 diameter aperture (m102 magnitude being measured in the F702W waveband); col. (7): standard T type; an undefined entry is given as −99.
TABLE 2

| ID (1) | S97 Number (2) | X (3) | Y (4) | $m_{F218}$ (5) | $m_{F218} - m_{F300}$ (6) | $m_{F218} - m_{F702}$ (7) | T Type (8) |
|-------|----------------|-------|-------|----------------|--------------------------|--------------------------|------------|
| 32……. | 497            | 139   | 768   | 20.66          | -0.56                    | -1.62                    | 4          |
| 60…….. | 230            | 734   | 458   | 20.44          | -0.45                    | -1.63                    | 10         |

Note—Col. (1): Object identifier; col. (2): cross-identification of objects against the catalog in Smail et al. 1997; col. (3): X centroid on the mosaicked F300W frame in pixels; col. (4): Y centroid on the mosaicked F300W frame in pixels; col. (5): 1/2 diameter aperture magnitude (STMAG) measured in the F218W waveband; col. (6): color in a 1/2 diameter aperture ($m_{F300}$ magnitude being measured in the F300W waveband); col. (7): color in a 1/2 diameter aperture ($m_{F702}$ magnitude being measured in the F702W waveband); col. (8): standard T type.

experiencing steady state star formation and possible UV-dominated spirals undergoing major starbursts is seen.

4. COMPARISON WITH A PRESENT-DAY CLUSTER POPULATION

As stressed above, the rest-frame mid-UV region—besides its higher sensitivity to the effect of age and metal content of old populations when compared to the optical—is quite sensitive to the presence of some amount of young stars, too (cf. Burstein et al. 1988). As a consequence, our newly obtained UV data provide a direct tool to investigate the present and past roles of star formation processes in cluster galaxies. This information is of paramount importance in the specific case of CL 0939+4713 because for the first time we can push our inquiry back in time up to an intermediate-redshift cluster population of ~5 billion years.

![Fig. 2](image_url)
Our analysis suggests several key points:

1. **UV Bright Galaxies in CL 0939+4713**: By simultaneously detecting UV-bright galaxies within the CL 0939+4713 field, we can infer the recent history of star formation in these galaxies. This is important for understanding the evolution of galaxy populations.

2. **Comparative Analysis**: Comparing our HST UV photometry with existing optical data, we can establish suitable models of populations (either purely old or hosting recent star formation). This allows us to establish whether signs of star formation activity among member galaxies persisted at the same, higher, or lower level when looking back at z ~ 0.4 (at least as far as the two galaxy samples are comparable).

3. **UV and Optical Data Integration**: For instance, the comparison with UV data of present-day galaxy clusters provides a direct way of verifying whether signs of star formation activity among member galaxies persist at the same, higher, or lower level, which cannot be directly observed from ground-based data.

4. **Multi-Wavelength Observations**: Our analysis involves multi-wavelength observations, which are crucial for distinguishing different populations of galaxies. In particular, the availability of balloon-borne mid-UV images of the nearby Coma Cluster obtained by Donas et al. (1995) make it obligatory to compare these data with our HST UV photometry and expected systematic errors of optical measurements are negligible.

5. **Heavy Observational Bias**: First, the FOCA aperture used to image the nearby Coma Cluster consists of a circular aperture of about 1'' in radius, while the three WF CCDs of the WFPC2 camera cover a field of 75'' × 75'' each. Even normalizing to the same angular diameter distance, it turns out that the UV data of Coma come from an FOV 18 times larger, whose radius exceeds by many times the cluster (X-ray) core radius (Briel, Henry, & 1992); conversely, our HST images of CL 0939+4713 rest frame by our own (m300, m702) HST magnitudes. In other words, since we are imaging the two clusters at the same rest-frame wavelengths, we are allowed to compare their populations, taking into account the relative distance modulus and a zero-point shift (estimated to be 0.65 mag) between HST and Donas et al.'s photometry alone (i.e., without applying the usual K-correction). Unlike the preliminary similar figure shown by Buson et al. (1998), field galaxies are now made distinguishable from those belonging to CL 0939+4713, while objects lacking a redshift estimate have been removed.

6. **Redshift Measurements**: Actually, when comparing the UV properties of the two populations superimposed in Figure 5 and spaced in redshift by an amount Δz ≈ 0.4, one should be fully aware of the heavy observational biases and limitations involved.

In summary, our analysis using HST UV photometry and optical ground-based photometry allows us to establish the last episode of star formation in UV-bright galaxies detected by WFPC2 and to compare these data with UV data of present-day galaxy clusters, providing a direct way of verifying whether signs of star formation activity among member galaxies persist at the same, higher, or lower level, which cannot be directly observed from ground-based data.
which can be assigned either to the cluster or the field population by means of a reliable redshift estimate is necessarily tiny, as yet (actually, as far as membership, i.e., redshift, determination is concerned, UV bright galaxies—presumably showing emission lines in their spectrum—are favored in comparison with random galaxies in the same field and, as such, are the objects for which the present ambiguity could be more easily removed by means of specific follow-up observing programs). Finally, when seen at CL 0939 + 4713 redshift, a significant fraction of a hypothetical galaxy population with UV properties identical to those of Coma Cluster elliptical galaxies would fall beyond the detection limit of the WFPC2 observations presented here, being too red (see Fig. 5). This is confirmed by the very low detection rate of early-type systems at \( z = 0.4 \), as only one of 13 E/S0s within the WFPC2 field listed as CL 0939 + 4713 members by Dressler et al. (1999) is detected in the UV.

As a consequence, the remarkably different portion of cluster population sampled by the two kinds of UV experiments, together with the poor absolute statistics of suitable cluster/field WFPC2 detections, prevent us from drawing any significant conclusion about possible large-scale population differences between CL 0939 + 4713 and Coma in the UV. The same is obviously true when comparing CL 0939 + 4713 and its own field. At this stage, one can simply notice that \( C-M \) diagrams of Figure 5 do not offer any evidence in favor of the presence—among the centrally located galaxy population of CL 0939 + 4713—of objects much bluer (i.e., UV brighter) than the bluest star-forming galaxies pervading the present-day Coma Cluster. This, in turn, suggests that the excess of star-forming objects noticed at \( z \approx 0.4 \) does not imply an enhanced star formation rate in individual galaxies. However, we want to stress once more that the possibility of quantifying the role of a large-scale phenomenon such as the Butcher-Oemler effect in the mid-UV is beyond the capabilities of the WFPC2 UV data of CL 0939 + 4713 discussed here.

5. COMPARISON WITH EVOLUTIONARY MODELS

As already pointed out, one can complement the above analysis by comparing the location within UV/optical \( C-M \) diagrams of our detected galaxies with that of suitable population models. In this way, one can estimate how frequently individual cluster galaxies are affected by major episodes of intervening star formation (up to continuous star formation processes, obviously indistinguishable from a very recent event). In the following, we restrict our analysis to spheroidal galaxies alone, i.e., avoiding young population-dominated spiral and/or irregular galaxies.

![Fig. 5.—UV/optical C-M diagrams superimposing CL 0939 + 4713 member galaxies (filled circles), CL 0939 + 4713 field galaxies (filled diamonds), and Coma Cluster galaxies (open circles), split into morphological classes. A relative distance modulus \( \Delta \mu = 6.47 \) is assumed to scale down UV/optical magnitudes \( (m_{\text{UV}}, b) \) of Donas et al. (1995) for Coma to our observed HST magnitudes \( (m_{300}, m_{702}) \). A further amount of 0.65 mag has been subtracted from \( b \) magnitudes to remove the zero-point mismatch between the two photometric systems [thus implying \( m_{300} = (b - 0.65) + 6.47 \), as well as \( (m_{300} - m_{702}) = (m_{\text{UV}} - b) + 0.65 \)]. Only UV bright galaxies for which an optical morphological classification is available are included. The shaded line represents the detection limit of WFPC2 observations. Formal errors of our HST UV photometry are shown by the representative error bar. Formal errors for HST optical measurements are negligible.](image-url)
Owing to their normally low or nonexistent star formation, elliptical galaxies are indeed the best tracers of episodic star formation events in clusters, such as might be caused by merging and/or tidal disturbances, intergalactic gas stripping and ram pressure, and so on.

Such a comparison is shown in Figure 6, where model spheroidal galaxies representing passively evolving populations with and without the addition of some amount of younger stars of different age are superimposed to our mid-UV/optical $C$-$M$ diagram for elliptical galaxies belonging to CL 0939 + 4713, its own field, and Coma (as seen at $z = 0.41$), respectively. More precisely, models on the right side of the figure represent aging single-burst populations at a fixed age of 10.8 Gyr (the estimated age of CL 0939 + 4713 when adopting $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0$, and $z_f = 5$). Only three representative galaxy masses ($10^{10}$, $10^{11}$, and $10^{12} M_\odot$, respectively) are shown here; a characteristic time $\tau$ corresponding to 0.1 times the Hubble time has been adopted for the initial starburst.

The fact that the UV/optical color of uncontaminated model galaxies in Figure 6 appears progressively redder and redder toward lower mass systems should be not surprising in view of the behavior of UV emission in old stellar populations. Our adopted chemospectrophotometric models (see Tantalo et al. 1996) indeed include the contribution of hot evolved sources such as hot horizontal branch stars and objects which avoid the Asymptotic Giant Branch phase (AGB-manqué stars), i.e., the hot components whose onset at late ages is responsible for the appearance of the well-known UV excess in elliptical galaxies. Since the amplitude of this phenomenon becomes higher and higher with growing galaxy mean metallicity (and total mass), one can straightforwardly realize why old, passively evolved spheroidal galaxies of higher total mass appear slightly bluer in their observed $(m_{300}-m_{702})$ color, an effect simply related to the higher level of UV-excess contamination affecting the sampled spectral region (around $2100 \text{ Å}$ at $z = 0.41$).

When recent episodes of star formation are added to the above models, the representative points of such “contaminated” populations move definitely toward the left (blue) portion of the CMD. In particular, our computations show the effect of adding to the model elliptical galaxies recent “rectangular” bursts with slightly different efficiencies $v_b$ (within 1%-3%) and constant duration ($10^8$ yr), centered at a time $\tau_b$ of 0.1, 0.4, and 0.8 Gyr before the epoch recorded by our observations, respectively.

One can recognize three major features when comparing UV observations and models:

![Figure 6](image-url)
1. Purely passively evolved populations fall beyond the detection capabilities of the UV observations discussed here (both WFPC2 and FOCA). The same is true for intermediate- and low-luminosity elliptical galaxies redder than $m_{300} - m_{702} \approx 3$ and $m_{300} - m_{702} \approx 2$, respectively, an observational bias giving rise to a growing spurious gap between less massive galaxy models and detected objects.

2. Secondary bursts experienced by galaxies earlier than 0.8 Gyr before the observing epoch are fully reabsorbed in terms of rest-frame mid-UV/optical colors, independently of galaxy mass and luminosity; this implies that all spheroidal galaxies UV bright enough to be detected in our HST F300W (as well as balloon-borne) images did host a starburst in the near past (typically 100–300 Myr earlier) or, alternatively, undergo a low-level, continuous star formation activity.

3. Among the numerous UV bright, early-type galaxies seen in Coma (and not at the center of CL 0939 + 4713), signs of very recent (and thus presumably frequent) star formation activity is shown preferentially by low-luminosity objects. In this respect, it is worth mentioning that the existence of this kind of continuous rejuvenation for Coma Cluster low-luminosity early-type galaxies (i.e., a series of overlapping short bursts) is largely supported also by recent spectroscopic observations (Caldwell & Rose 1998), showing that a significant fraction of these faint members do host a young population superposed to older stars.

6. LOOKING AT CL 0939 + 4713 IN THE FAR-UV

As already pointed out, our HST observations aimed also at exploring the far-UV portion of the rest-frame energy distribution of galaxies at $z \sim 0.4$. Actually, the presence of a far-UV excess (upturn) in metal-rich evolved populations has been known since the early epochs of UV space astronomy (Code 1969; Code & Welch 1979; Bertola et al. 1980, 1986; Bertola, Capaccioli, & Oke 1982; Oke, Bertola, & Capaccioli 1981), and the goal of recording its onset and subsequent evolution at intermediate redshift is still a major observational challenge (see Greggio & Renzini 1999 and O’Connell 1999 for comprehensive recent reviews).

In particular, on the basis of current galaxy evolutionary models (e.g., Bressan, Chiosi, & Fagotto 1994; Tantalo et al. 1996), one should expect that—owing to the vanishing of post-HB evolutionary paths (post–early AGB stars, AGB-manqué stars) which generate most of the present-day UV bright stars—the UV properties of old populations in giant ellipticals do show a dramatic change when observed to a proper look-back time (which could well fall around CL 0939 + 4713 redshift). In other words, looking back in time a few billion years, one should witness some kind of “switching off” of the UV-upturn seen in present-day giant ellipticals, thus recording rest-frame 1550–$V$ colors much redder than their present value.

Unfortunately, the rest-frame far-UV emission (F218W) of almost the totality of galaxies detected in the rest-frame mid-UV (F300W) could not be recorded, and even the upper limits to the level of the far-UV flux in individual ellipticals at $z = 0.4$ implied by our WFPC2 observations are too high to provide the sought astrophysical constraints. More precisely, the upper limit to the UV emission imposed by adding F218W counts in the total frame area occupied by the whole sample of optically bright ellipticals in the corresponding F702W frames imply that one cannot detect objects (at 3 $\sigma$ limit) whose rest-frame UV/optical color is higher (i.e., redder) than $(1550 - V) = 1.0$. Such a (blue) color can be reached among present-day galaxies only by actively star-forming systems, while even the nearby UV brightest old populations in ellipticals are not bluer than $(1550 - V) \sim 2$ and, as such, could not be detected (cf. Burstein et al. 1988).

As a consequence, the set of (F218W) UV data discussed here is inadequate to establish the existence and amplitude of the UV-upturn phenomenon typical of present-day evolved populations at CL 0939 + 4713 look-back time. This outcome is consistent with similar inconclusive results reached by other groups who observed clusters at similar distances with the same instrumental configuration (e.g., Renzini 1996). This conclusion, though negative, does not imply that such an investigation is strictly beyond HST capabilities, however, and is presently pushing other groups to explore alternative observing approaches. In this respect, the very recent positive result of Brown et al. (1998), who were able to sample the UV upturn of a few elliptical galaxies belonging to a cluster of similar redshift (Abell 370; $z = 0.375$) by combining two FOC long-pass filters, holds the hope of successfully exploiting HST in the near future, in particular with the planned installation of the Advanced Camera for Surveys (ACS).

7. CONCLUSIONS

This work can be considered as the first “journey” into the rest-frame UV of an intermediate-redshift, rich galaxy cluster. Making use of HST, we were able to detect in a single WFPC2 field tens of UV bright sources belonging either to CL 0939 + 4713 or to its close foreground/background. Newly obtained UV data have been combined with preexisting HST and ground-based optical images to derive unprecedented UV/optical C-M and two-color diagrams. While irregular and (luminous) early-type galaxies are well confined to specific color ranges within such diagrams, spirals do exhibit quite a large variability in color.

In order to explore possible evolutionary effects, HST data of CL 0939 + 4713 have been finally compared with balloon-borne UV data of the local Coma Cluster. Although an exhaustive comparison of the hottest populations of nearby and intermediate-redshift clusters has to wait until deeper, wide-field UV surveys of distant clusters become available, the limited data sets discussed here do provide interesting pieces of evolutionary information. For instance, no hints of a fast evolution in the UV from $z \sim 0.4$ to the present time (in the sense of cluster galaxies at $z \sim 0.4$ hosting a star formation activity dramatically higher than their present-day counterparts) are found.

REFERENCES

Andreon, S., Davoust, E., & Heim, T. 1997, A&A, 323, 337
Belloni, P., Bruzual, A. G., Thimm, G. J., & Röser, H.-J. 1995, A&A, 297, 61
Belloni, P., & Röser, H.-J. 1996, A&AS, 118, 65
Bertola, F., Capaccioli, M., Holm, A. V., & Oke, J. B. 1980, ApJ, 237, L65
Bertola, F., Capaccioli, M., & Oke, J. B. 1982, ApJ, 254, 494
Bertola, F., Gregg, M. D., Gunn, J. E., & Oemler, A. Jr. 1986, ApJ, 303, 624
Bressan, A., Chiosi, C., & Fagotto, F. 1994, ApJS, 94, 63
Briel, U. G., Henry, J. P., & Böhringer, H. 1992, A&A, 259, L31
Brown, T. M., Ferguson, H. C., Déharveng, J.-M., & Jedrzejewski, R. I. 1998, ApJ, 508, L139
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, R. L. 1988, ApJ, 328, 440
Caldwell, N., & Rose, J. 1998, ApJ, 508, L139
Buson, L. M., Bertola, F., Cappellari, M., Chiosi, C., Dressler, A., & Oemler, A. 1998, in ASP Conf. Ser. 146, The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift, ed. S. D’Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 488
Butcher, H., & Oemler, A. 1978, ApJ, 219, 18
———. 1984, ApJ, 285, 426
Caldwell, N., & Rose, J. A. 1998, AJ, 115, 1423
Code, A. D. 1969, PASP, 81, 475
Code, A. D., & Welch, G. A. 1979, ApJ, 228, 95
Cornett, R. H., et al. 1998, AJ, 116, 44
Couch, W. J., Barger, A. J., Smail, I., Ellis, R. S., & Sharples, R. M. 1998, ApJ, 497, 188
Couch, W. J., Ellis, R. S., Sharples, R. M., & Smail, I. 1994, ApJ, 430, 121
Donas, J., Milliard, B., & Laget, M. 1995, A&A, 303, 661
Donas, J., Viton, M., Martin, C., & Milliard, B. 1997, in The Ultraviolet Universe at Low and High Redshift: Probing the Progress of Galaxy Evolution, ed. W. H. Waller, M. N. Fanelli, J. E. Hollis, & A. C. Danks (New York: AIP), 105
Dorman, B., & O’Connell, R. W. 1997, in The Ultraviolet Universe at Low and High Redshift: Probing the Progress of Galaxy Evolution, ed. W. H. Waller, M. N. Fanelli, J. E. Hollis, & A. C. Danks (New York: AIP), 175
Dressler, A., et al. 1997, ApJ, 490, 577
Dressler, A., & Gunn, J. E. 1983, ApJ, 270, 7
———. 1992, ApJS, 78, 1
Dressler, A., Oemler, A., Jr., Butcher, H. R., & Gunn, J. E. 1994a, ApJ, 430, 107
Dressler, A., Oemler, A., Gunn, J. E., & Butcher, H. R. 1993, ApJ, 404, L45
Dressler, A., Oemler, A., Jr., Sparks, W. B., & Lucas, R. A. 1994b, ApJ, 435, L23
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H. R., Couch, W. J., Ellis, R. S., & Oemler, A., Jr. 1999, ApJS, 122, 51
Fukugita, M., Doi, M., Dressler, A., & Gunn, J. E. 1995, ApJ, 439, 584
Greggio, L., & Renzini, A. 1999, Mem. Soc. Astron. Italiana, 70, 691
Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065
Hutchings, J. B., & Davidge, T. J. 1997, PASP, 109, 667
O’Connell, R. W. 1999, ARA&A, 37, 603
Oemler, A., Jr., Dressler, A., & Butcher, H. R. 1997, ApJ, 474, 561
Oke, J. B., Bertola, F., & Capaccioli, M. 1981, ApJ, 243, 453
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A., Butcher, H. R., Ellis, R. S., & Oemler, A., Jr. 1999, ApJ, 518, 576
Renzini, A. 1996, in Proc. STScI Symp. (December 1995), Science with HST-II, ed. P. Benvenuti, F. Macchetto, & E. Schreier (Baltimore: STScI), 267
Schindler, S., Belloni, P., Ikebe, Y., Hattori, M., Wambsganss, J., & Tanaka, Y. 1998, A&A, 338, 843
Schindler, S., & Wambsganss, J. 1996, A&A, 313, 113
Seitz, C., Kneib, J.-P., Schneider, P., & Seitz, S. 1996, A&A, 314, 707
Smail, I., Dressler, A., Couch, W. J., Ellis, R. S., Oemler, A., Jr., Butcher, H., & Sharples, R. M. 1997, ApJS, 110, 213
Stanford, S. A., Eisenhart, P. R. M., & Dickinson, M. 1995, ApJ, 450, 512
———. 1998, ApJ, 492, 461
Tantalo, R., Chiosi, C., Bressan, A., & Fagotto, F. 1996, A&A, 311, 361