FAR-ULTRAVIOLET EMISSION FROM ELLIPTICAL GALAXIES AT $z = 0.33$

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ABSTRACT

We present far-UV images of the rich galaxy cluster ZwCl 1358.1+6245, taken with the Space Telescope Imaging Spectrograph on board the Hubble Space Telescope (HST). When combined with archival HST observations, our data provide a measurement of the UV-to-optical flux ratio in eight early-type galaxies at $z = 0.33$. Because the UV flux originates in a population of evolved, hot, horizontal-branch (HB) stars, this ratio is potentially one of the most sensitive tracers of age in old populations—it is expected to fade rapidly with look-back time. We find that the UV emission in these galaxies, at a look-back time of 3.9 Gyr, is significantly weaker than it is in the current epoch, yet it is similar to that in galaxies at a look-back time of 5.6 Gyr. Taken at face value, these measurements imply different formation epochs for the massive elliptical galaxies in these clusters, but an alternative explanation is a “floor” in the UV emission due to a dispersion in the parameters that govern HB morphology.

Subject headings: cooling flows — galaxies: evolution — galaxies: stellar content — ultraviolet: galaxies

1. INTRODUCTION

Elliptical and S0 galaxies show a striking rise in their spectra at $\lambda < 2000$ Å. Spectroscopy (Brown et al. 1997) and imaging (Brown et al. 2000b) of local galaxies show that this “UV upturn” arises from a minority population of hot horizontal-branch (HB) stars. On energetic grounds, these evolved stars were long considered the best candidates for the UV emission (Greggio & Renzini 1990), with the implication that the UV-to-optical color could be the most rapidly evolving feature in the spectra of elliptical galaxies. In theory, the UV upturn can fade by several magnitudes as the look-back time increases by a few gigayears, but the evolution is very model-dependent, and a strong UV upturn could appear at ages as early as $\sim 6$ Gyr (Tantalo et al. 1996) or as late as $\sim 15$ Gyr (Yi, Demarque, & Oemler 1998).

This evolution has motivated our ongoing survey to measure the UV upturn in clusters at intermediate redshifts. Previously, we observed the rich clusters Abell 370 at $z = 0.375$ (Brown et al. 1998) and CL 0016+16 at $z = 0.55$ (Brown et al. 2000a); those observations implied that there was little fading of the UV upturn out to $z \approx 0.4$ with a significant decline at higher $z$. However, further cluster measurements are clearly needed to explore the universality of this evolution.

To that end, we have obtained far-UV images of ZwCl 1358.1+6245 with the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST). This is a rich, compact cluster of galaxies originally identified by Zwicky & Herzog (1968, p. 125) and later rediscovered in the X-ray observations of Luppino et al. (1991). It lies at intermediate redshift ($z = 0.33$; Fisher et al. 1998) with little foreground extinction ($E_{B-V} = 0.023$ mag; Schlegel, Finkbeiner, & Davis 1998). When combined with archival images from the Wide Field Planetary Camera 2 (WFPC2) on HST, our far-UV images provide a measurement of the UV upturn for eight elliptical and S0 galaxies in the cluster core. Seven of these galaxies are well detected (>3 $\sigma$) in the far-UV, and the central galaxy shows strong extended UV emission, likely associated with infalling matter. The weak UV upturn measured in these galaxies is in contrast to the strong UV upturn measured previously at $z = 0.375$, yet surprisingly similar to that at $z = 0.55$.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Far-UV Imaging

We imaged ZwCl 1358.1+6245 for 68,291 s while the cluster was in the HST Continuous Viewing Zone. The field was centered at R.A. = 13$^h$59$^m$50.63, decl. = 62$^\circ$31’57” (J2000) with a position angle of 50°, placing eight S0 and elliptical galaxies within the STIS 25” × 25” field, including the brightest galaxy of the cluster (see Fig. 1). Exposures were dithered by 1–2 pixels to allow removal of hot pixels. We used the F25QTZ filter (1450–1900 Å) to minimize the background from geocoronal emission in H α (1216 Å and O i λλ1304. Note that the sensitivity of the far-UV camera has been slowly decreasing at the rate of $\sim 1.5\%$ yr$^{-1}$; we include this decline in our analysis (at the time of our observations, a flat spectrum of 1.19 × 10$^{-6}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ produced 1 count s$^{-1}$ in this bandpass).

The STIS far-UV detector has a very low dark rate when cold ($\sim 6 \times 10^{-6}$ counts s$^{-1}$ pixel$^{-1}$), but as observations progress, a dark count “glow” appears, centered in the upper left-
hand quadrant of the detector. Using the optical images to mask objects, we normalized and subtracted from each exposure a profile of this dark glow (created from a sum of dark exposures). We co-added the exposures using the IRAF DRIZZLE package, weighting the pixels in each frame by the ratio of the exposure time squared to the dark count variance, including a hot pixel mask. The algorithm weights the exposures by the square of the signal-to-noise ratio for sources fainter than the background. Note that the STIS UV detectors are photon counters that register less than 1 count per cosmic-ray hit, and thus the images do not require the cosmic-ray rejection required for processing CCD images.

2.2. Optical Data

We used the DRIZZLE package to co-add the archival WFPC2 images of this cluster, reject cosmic rays and hot pixels, and register the co-added optical data to the far-UV image. WFPC2 data in the F606W (broad V) and F814W (I) bandpasses were available for our entire field; these data come from an impressive mosaic of the cluster by van Dokkum et al. (1998), who also provide morphological classifications for the galaxies in our sample (Table 1). Partial coverage of our field was also available in F450W (B). The UV upturn strength is usually measured by the rest-frame $m_{1550}-V$ color, in which the flux from 1250 to 1850 Å gives $m_{1550}$ and in which $V$ is Johnson V. Our far-UV bandpass corresponds to 1090–1429 Å in the rest frame, while the F814W bandpass corresponds roughly to Johnson V in the rest frame. In § 2.5, we will use the spectral energy distributions of local elliptical galaxies, redshifted to $z = 0.33$, to interpret the observed count rates in these bandpasses as $m_{1550}-V$ colors.

2.3. Extended Emission

Due to their low luminosity and sharp profile in the far-UV, elliptical galaxies usually appear pointlike in images of distant clusters. What is striking about Figure 1 is the appearance of the brightest cluster member, which shows extended tenuous emission that is not seen in the broad WFPC2 bandpasses at longer wavelengths. The cluster shows significant X-ray luminosity (Stocke et al. 1991) and associated Hα emission (Donahue, Stocke, & Giola 1992). The Hα contours extend outward from the nucleus in three prongs, and two of these trace the far-UV emission when the Donahue et al. (1992) image is aligned to our own, strongly suggesting that the far-UV emission is due to Lyα redshifted into the STIS far-UV bandpass. The X-ray and Hα emission were historically taken as evidence of a “cooling flow,” although the presence of cooling gas is now controversial, and this term may be a misnomer. Lyα emission is expected to trace the Hα emission in galaxy clusters, whether or not the infalling material is cooling in the historical sense, but it is rarely seen because this emission is lost in the geocoronal Lyα emission when observing local clusters. Unfortunately, both the Lyα emission and the stellar light peak toward the center of this galaxy, so it is difficult to separately quantify the two.

Another, less likely, source would be star formation from the infalling material. Normalizing a model spectrum of constant star formation to the far-UV emission, we find that such star formation would be difficult to detect in the optical images. In any case, the optical images show no evidence of the morphology seen in the far-UV.

2.4. Photometry

We performed aperture photometry on the far-UV image using our own IDL software, with a source aperture of radius 16 pixels (0.4′) and a sky annulus of radii 80 and 100 pixels, as done previously by Brown et al. (2000a). Each aperture was centered on the bright core of the galaxy, determined from the F814W WFPC2 data. Statistical errors for the photometry include the Poisson contribution from the source counts, the statistical uncertainties in the spatially varying background, and the effects of the weighted co-addition of the frames (see the previous section). Using the DAOPHOT package in IRAF, we measured the flux in the F814W data (registered via DRIZZLE to the far-UV frame) using the same source and sky apertures. The optical and far-UV photometry are shown in Table 1.

Note that the aperture size does not contribute significant systematic errors in our analysis, whether we are considering measurements at different $z$ or in different bandpasses. Except for galaxy 375 (which has extended emission), there is little variation in our $m_{1550}-V$ colors as we reduce the aperture size—they remain uniformly red, with small variations consistent with the statistical uncertainties in Table 1. Measurements of $m_{1550}-V$ in local elliptical galaxies (Burstein et al. 1988) were performed with a 10′′ × 20′′ aperture, while our 0.8′′ diameter aperture would subtend ∼50′′ at the distance of Virgo (characteristic of the Burstein et al. sample). However,
in local galaxies, there is almost no variation in the surface \( m_{1550} - V \) color out to a radius of \( \sim 20'' \) (Ohl et al. 1998), and the colors within any aperture are dominated by the core (given the sharply peaked profiles). We also note that in the HST bandpasses, our aperture results in encircled energy agreement at the 5% level for point sources, and better agreement for extended sources (R. Robinson 1997\(^2\); Holtzman et al. 1995).

2.5. UV-to-Optical Colors

The UV upturn is traditionally characterized by the rest-frame \( m_{1550} - V \) color (see Burstein et al. 1988). We used the spectra of three local elliptical galaxies (NGC 1399, M60, and M49) to convert the observed STIS and WFPC2 count rates to rest-frame \( m_{1550} - V \) colors, as done previously in Brown et al. (1998, 2000a). Our spectra of NGC 1399, M60, and M49 have respective \( m_{1550} - V \) colors of 2.05, 2.24, and 3.42 mag (Burstein et al. 1988); despite the substantial range in UV upturn strength, the spectral shape within the far-UV range or within the optical range varies little from galaxy to galaxy. We redshifted these local templates to \( z = 0.33 \) and then applied a foreground reddening of \( E(B-V) = 0.023 \) mag (Schlegel et al. 1998). We then used the IRAF CALCPHOT routine to calculate the relative count rates for these templates in the STIS/far-UV and WFPC2/F814W bandpasses. The ratios of far-UV to F814W count rates observed in the ZwCl 1358.1+6245 galaxies \( (R_{\text{obs}}) \) were then compared with the ratios from the templates \( (R_{\text{template}}) \), and the template with the closest ratio was used to determine the rest-frame \( m_{1550} - V \) color (Table 1), using the relation

\[
(\text{m}_{1550} - \text{V})_{\text{obs}} = (\text{m}_{1550} - \text{V})_{\text{template}} - 2.5 \log (R_{\text{obs}}/R_{\text{template}}).
\]

Except for galaxy 375, all of the galaxies show weak UV upturn emission. Galaxy 375 is contaminated by the Ly\(\alpha\) emission discussed previously, so the UV upturn emission is really an upper limit on the emission from the evolved HB population. Note that in a much smaller aperture (radius 5 pixels) that excludes much of the Ly\(\alpha\) emission, this galaxy has an even bluer \( m_{1550} - V \) of 1.6 mag.

We show in Figure 2 the \( m_{1550} - V \) colors measured in galaxy clusters to date. Nearby quiescent elliptical galaxies have been measured by Burstein et al. (1988) in Virgo, Coma, and Fornax. The galaxies at \( z = 0.33 \) are from the present work (excluding galaxy 375). Measurements at \( z = 0.375 \) are from Faint Object Camera (FOC) observations of Abell 370 (Brown et al. 1998). Measurements at \( z = 0.55 \) are from STIS observations of CL 0016+16 (Brown et al. 2000a). At each redshift, the observed fluxes have been transformed to rest-frame \( m_{1550} - V \) using the spectra of local elliptical galaxies.

Before proceeding, it is worth noting that the \( z = 0.375 \) data may have significant systematic errors—the calibration on the FOC was far less certain than it is with STIS. The measurements at \( z \approx 0, z = 0.33, \) and \( z = 0.55 \) were all done with distinct photometry in the far-UV and optical, whereas the FOC measurements come from the ratio of two long-pass filters (see Brown et al. 1998). It would be prudent to verify the \( m_{1550} - V \) colors at \( z = 0.33 \) with a true solar-blind instrument, such as STIS or the far-UV channel on the Advanced Camera for Surveys, to verify that the UV upturn is so strong in Abell 370.

3. DISCUSSION

To place our observations in context, we have plotted in Figure 2 the colors measured in galaxy clusters to date. Nearby quiescent elliptical galaxies had to be completed at \( z = 0 \), followed by quiescent galaxies had to be completed at \( z = 0.33 \), implying a surprisingly large spread in colors bounded by models at \( z = 0 \) and \( z = 0.33 \), and, more importantly, the similarity between the measurements at \( z = 0.33 \) and \( z = 0.55 \), imply a surprisingly large dispersion in the formation epochs between clusters (\( z_f \approx 2-4 \)). Such variation in \( z_f \) would be more plausible if the non-monotonic evolution in \( m_{1550} - V \) implied by the FOC measurements were independently confirmed.

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\(^2\) Examining the STIS Point-Spread Function (http://hires.gsfc.nasa.gov/stis/postcal/quick_reports).
Another (less likely) explanation for the variation in Figure 2 is that there is a small dispersion in $z$, among the clusters, but the chemical evolution varied significantly from cluster to cluster. The onset of the UV upturn in the Tantalo et al. (1996) models depends on the details of the chemical evolution, and the UV upturn in local elliptical galaxies correlates strongly with metallicity and, to a lesser extent, with luminosity (Burstein et al. 1988). However, all of the galaxies in these programs are massive elliptical galaxies in the centers of rich, massive clusters—it seems unlikely that their populations would be chemically distinct from their analogs in the local universe. Even so, it would be interesting to obtain metallicity measurements for our sample, to look for trends like those seen locally.

Models for the evolution of elliptical galaxies are sensitive not only to $z$, but to other parameters, such as the time of onset for galactic winds, accretion timescale, and efficiency of star formation. Tantalo et al. (1996) tuned these parameters to reproduce the properties of low-$z$ elliptical galaxies, and there is not much freedom to tune them further to match our observed UV evolution. It is therefore worth looking at the parameters that affect HB morphology in particular. Hot HB stars have lost nearly all (but not all) of their envelope as a result of mass loss on the red giant branch (RGB). Tantalo et al. (1996) make specific assumptions about the relation between mass loss and chemical abundance in order to approximate the UV upturn range at $z = 0$. In their models, hot HB stars do not exist at higher $z$ because their main-sequence progenitors have larger masses (resulting in redder HB stars). What if, instead, we imagine that at $z = 0$ there is a reservoir of stars in elliptical galaxies that have lost so much mass that they fail to ignite He? See, e.g., Figure 9 in Greggio & Renzini (1990). These stars could, for example, come from the high-metallicity tail of the metallicity distribution. At higher $z$, the more massive stars in that metallicity range would become hot HB stars, providing the UV flux that would otherwise be missing. Therefore, moving from zero to high redshift, the UV upturn would be produced by stars at progressively higher metallicity, until it disappears entirely when the very end of the metallicity distribution is reached. In more general terms, the same qualitative behavior is expected if the occurrence of hot HB stars is driven by a distribution of stellar ages or a distribution of RGB mass loss, or a combination thereof. It is plausible that the details of the metallicity distribution, and the relation between mass loss and RGB parameters, could be tuned to reproduce the gradual $m_{1550} - V$ evolution observed, with a common $z_f \sim 4$, without violating other constraints on stellar evolution.

Further alternatives are also possible. At $z = 0$, hot HB stars may be the dominant, but not the sole, contributor to the UV upturn. While the hot HB would rapidly disappear with redshift, the $m_{1550} - V$ color would initially drop, but it would hit a floor value as the role of dominant UV contributor is assumed by another class of UV-bright objects whose evolution with redshift is not as fast as that of the hot HB stars. Possibilities include a low level of ongoing (massive) star formation and various kinds of binaries such as, e.g., post-RGB binary components and accreting white dwarfs (Greggio & Renzini 1990). If future observations can show that HB stars are not the sole contributor to the UV upturn at $0.3 \leq z \leq 0.6$, the Tantalo et al. (1996) models would imply $z_f \approx 2$; however, given that Kodama et al. (1998) and Stanford et al. (1998) find the bulk of the stellar population formed at $z \geq 3$, such a finding would more likely tell us that the onset of the UV upturn takes place at an older age than the $\sim 6$ Gyr given by the models of Tantalo et al. (1996).

It would be difficult to rule out a low star formation rate (SFR) as the source of the $m_{1550} - V$ floor. Assuming constant star formation with a flat $f_0$ spectrum, the Kennicutt (1998) relation gives $SFR = 1.4 \times 10^{-28} L_\odot \approx 0.005 - 0.02 \ M_\odot \ yr^{-1}$ for our $z = 0.33$ sample (excluding galaxies 375 and 357). This is a lower limit, given that the real spectrum would likely have a far-UV downturn due to extinction. The rates in the galaxies at $z = 0.55$ are similar (0.008–0.015 $M_\odot \ yr^{-1}$). Thus, from $z = 0.6$ to $z = 0.3$ (a span of 2.4 Gyr), this SFR would produce $\sim 3 \times 10^7 \ M_\odot$ of stars, which would be at least 3.6 Gyr old today if the star formation stopped at $z = 0.3$. A remnant intermediate-age population comprising a few percent of the total stellar mass in a normal elliptical galaxy would be difficult to detect. The same arguments apply if the star formation is episodic because the number of greater than 3 $\sigma$ detections at $z = 0.33$ (excluding galaxy 375) and $z = 0.55$ implies a duty cycle of $\sim 80\%$. This hypothesis could be tested by searching for low levels of Hα or O II emission.

In summary, our findings are in broad agreement with the expectation of a fading UV upturn with redshift because of a progressively smaller number of hot HB stars being produced in younger populations. However, the rate of this fading remains to be understood—whether the whole trend can be attributed to the redshift evolution of the number of hot HB stars or whether an additional class of hot stars is contributing a floor to the UV flux that is minor at $z = 0$ but already dominant at $z \sim 0.3$.

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