MEASUREMENTS OF FAR-UV EMISSION FROM ELLIPTICAL GALAXIES AT $z = 0.375$

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ABSTRACT

The “UV upturn” is a sharp rise in spectra of elliptical galaxies shortward of rest-frame 2500 Å. It is a ubiquitous phenomenon in nearby giant elliptical galaxies and is thought to arise primarily from low-mass evolved stars on the extreme horizontal branch and beyond. Models suggest that the UV upturn is a very strong function of age for these old stellar populations, increasing as the galaxy gets older. In some models, the change in UV/optical flux ratio is a factor of 25 over timescales of less than 3 Gyr. To test the predictions for rapid evolution of the UV upturn, we have observed a sample of normal elliptical galaxies in the $z = 0.375$ cluster Abell 370 with the Faint Object Camera aboard the Hubble Space Telescope. A combination of two long-pass filters was used to isolate wavelengths shortward of rest-frame 2700 Å, providing a measurement of the UV upturn at a lookback time of approximately 4 Gyr. Surprisingly, the four elliptical galaxies observed show a range of UV upturn strength that is similar to that seen in nearby elliptical galaxies, with an equivalent $m_{1550} - V$ color ranging from 2.9 to 3.4 mag. Our result is inconsistent with some models for the UV upturn; other models are consistent only for a high redshift of formation ($z_f \geq 4$).

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: stellar content — ultraviolet: galaxies — ultraviolet: stars

1 INTRODUCTION

The spectra of elliptical galaxies and spiral galaxy bulges exhibit a strong upturn shortward of 2500 Å, dubbed the “UV upturn.” The phenomenon was among the first major discoveries in UV extragalactic astronomy, and the implied existence of a hot stellar component in elliptical galaxies appeared to contradict the traditional picture of these galaxies as old, cool, passively evolving populations. The pioneering UV observations—with OAO (Code & Welch 1979) and IUE (Bertola, Capaccioli, & Oke 1982)—could only sample the Rayleigh-Jeans tail of the UV spectrum ($\lambda > 1200$ Å) with poor signal-to-noise ratios and resolution. Thus, early explanations for the UV upturn included young massive stars, extreme horizontal branch (EHB) stars, post-asymptotic giant branch (PAGB) stars, and several binary scenarios (Greggio & Renzini 1990). Eventually, it became clear that the phenomenon was likely due to the presence of hot evolved stars (see Greggio & Renzini 1990; Bressan, Chiosi, & Fagotto 1994; Horch, Demarque, & Pinsonneault 1992), and thus the UV upturn is still consistent with the picture of elliptical galaxies as passively evolving populations. Observational evidence for this view was found in the spectra from the Hopkins Ultraviolet Telescope (HUT) (Ferguson et al. 1991; Brown et al. 1997); these spectra are reproduced well by a composite population of EHB, post-EHB, and PAGB stars.

Characterized by the $m_{1550} - V$ color, the UV upturn varies strongly (ranging over 2.05–4.50 mag) in nearby quiescent early-type galaxies (Bertola et al. 1982; Burstein et al. 1988), even though the spectra of elliptical galaxies at longer wave-lengths are qualitatively very similar. The $m_{1550} - V$ color is positively correlated with the strength of Mg$_2$ line absorption (i.e., bluer at higher line strengths), opposite to the behavior of optical color indices; it also correlates with velocity dispersion and luminosity but to a weaker extent (Burstein et al. 1988).

The UV upturn is thought to “turn on” when the stars in an elliptical galaxy are of sufficient age to populate the extreme horizontal branch (see Greggio & Renzini 1990; Bressan et al. 1994). After leaving the EHB, the post-EHB stars become hotter and brighter before descending the white dwarf cooling curve (see Dorman, Rood, & O’Connell 1993). EHB stars and their associated post-EHB phases are considerably longer lived than the bright PAGB stars originating on the red end of the horizontal branch (HB). Thus, they can dominate the spectrum of an elliptical galaxy despite their minority status in the stellar population. The varying fraction of EHB stars in the nearby elliptical populations may drive the variation in the strength of the UV upturn (see Brown et al. 1997, and references therein).

Because the main-sequence turnover mass and HB morphology are sensitive to the age of a passively evolving population, evolution theory predicts that the UV upturn should fade with lookback time, with the amount of fading depending upon the mechanisms driving HB morphology and the redshift of formation. The UV upturn may be the most rapidly evolving feature in elliptical galaxies (see Greggio & Renzini 1990). Several previous attempts to measure the UV upturn at intermediate redshifts, using UV imaging and spectroscopy with the Hubble Space Telescope (HST), have been inconclusive (e.g., Windhorst et al. 1994; Renzini 1996; Buson et al. 1998). We have observed the cluster Abell 370 (at $z = 0.375$) with the hope of measuring the UV upturn at an epoch considerably younger than our own; the lookback time for this redshift is 4 Gyr (we assume a cosmology of $H_0 = 67$ km s$^{-1}$, $q_0 = 0.05$, and $\Lambda = 0$ throughout this Letter). We used a combination of long-pass filters in the Faint Object Camera (FOC) aboard HST to create a synthetic bandpass with high UV throughput. Our four fields were each centered on one or two giant elliptical galaxies, although fainter companions are also included in the...
images. The galaxies under study are all cluster members, as confirmed via ground-based spectroscopy, and show no spectroscopic indications of star formation (Souchail et al. 1988). Their $U-V$ colors are consistent with passive evolution (MacLaren, Ellis, & Couch 1988). Morphological classification is confirmed by Couch et al. (1994), using the Wide Field and Planetary Camera 1, and by Wide Field and Planetary Camera 2 archival images (ID No. 6003).

2. OBSERVATIONS

Over the course of 1997, we observed four fields in Abell 370 plus two calibration stars (Table 1). The cluster fields were chosen to place at least one bright giant elliptical galaxy in the center of each image. Fields 1, 2, 3, and 4 are centered on galaxies BOW 9, 10, 24, and 34, respectively (Butcher, Oemler, & Davis 1998). BOW 24 is actually two elliptical galaxies, and so we refer to them as 24a and 24b; 24b is 2\degree directly south of 24a. The fields suffer from little foreground extinction: $E(B-V) \leq 0.03$ mag (Burstein & Heiles 1984; Schlegel, Finkbeiner, & Davis 1998).

The FOC is a photon-counting imager with a high sensitivity at the short end of the HST wavelength range. Our use of the $512 \times 1024$ zoomed format provided the full 14\arcsec $\times$ 14\arcsec field of view at the expense of the full dynamic range available in the FOC. The F130LP and F370LP filters are designed to block light shortward of 1300 and 3700 \AA, respectively. Longward of the cutoff wavelength, the transmittance of each filter rapidly rises to a value that is nearly wavelength independent (0.92 in F130LP and 0.83 in F370LP); the ratio of the light detected in each filter is extremely sensitive to the flux shortward of 3700 \AA and insensitive to the shape of a spectrum longward of 3700 \AA. This wavelength corresponds to 2690 \AA in the rest frame of Abell 370, and thus these filters are useful for measuring the UV upturn at this redshift.

All of our images were processed via the standard pipeline, which includes dezooming, geometric correction, and flat-fielding. FOC images also contain reseau marks where the flux is suppressed but not corrected in the pipeline. Before registering and co-adding our images, we corrected the reseau marks by interpolating from neighboring unaffected pixels. The affect of our reseau correction is very small because the individual frames were shifted by several pixels and because no reseau marks fell near the core of any galaxy of interest.

Unfortunately, one of the bright companion galaxies, BOW 58, fell behind one of the FOC occulting “fingers” in the image containing BOW 10. Also, our FOC images demonstrate that BOW 9, the central galaxy of frame 1, is a close superposition of two galaxies—a giant elliptical and a small bright companion. Because the small companion is so close to the giant elliptical galaxy, we cannot disentangle their UV light, and so we exclude BOW 9 from our analysis at this time.

3. PHOTOMETRY

We used the IRAF routine PHOT to perform aperture photometry on the bright elliptical galaxies in our images. The point-spread functions of the two filters are similar, and so taking the ratio of the F130LP count rate to the F370LP count rate requires no aperture correction, given a suitably large aperture; our aperture has a radius of 65 pixels (0\arcsec91). The background annulus was chosen to avoid neighboring galaxies. The annulus inner and outer radii were 164 and 195 for BOW 10; for the other galaxies, the radii were 145 and 165.

Our large apertures enclose practically all of the detectable UV light in these galaxies. Sixty-five FOC pixels correspond to 4.55 kpc at $z = 0.375$. Compared to the IUE and HUT apertures used to measure the UV light in nearby elliptical galaxies, our apertures are quite large. In their survey of the UV upturn in nearby galaxies, Burstien et al. (1988) matched the $10\arcsec \times 20\arcsec$ IUE aperture with a 7\arcsec radius aperture in the optical; 7\arcsec subtends 0.85 kpc at the distance of NGC 1399, and so the equivalent aperture radius at $z = 0.375$ would be 12 FOC pixels. Although we note the UV light extends significantly beyond 12 FOC pixels, for comparison to nearby elliptical galaxies, we also performed our photometry with this smaller aperture (but with no change in the sky annulus); this gives an indication of the nuclear UV upturn strength in the Abell 370 elliptical galaxies. Table 2 gives the FOC count rates in both the large and small apertures. Statistical errors are all on the order of 1%.

Photometry on the star G158-100 demonstrates that the FOC throughputs are in agreement with expectations. We extended the optical (3200–9200 \AA) spectrum of this white dwarf (Colina & Bohlín 1994; Oke 1990) into the UV using a Kurucz (1992) synthetic spectrum with parameters $T_{\text{eff}} = 5250$ K, $\log g = 5$ (the maximum available in the Kurucz grid), and $[\text{Me/H}] = -3.0$. Laird, Carney, & Latham (1988) quote a somewhat cooler temperature of 5072 K and a metallicity of $-2.82$, but we found that our choice of parameters gave the best agreement with the optical spectrum. Note that the surface gravity in the model has a negligible effect for our purposes here. Using the IRAF/STSDAS routine CALCCHOT in the SYNPHOT pack-
These templates thus reproduce the flux and in the 5000–6200 Å region. Because the optical and UV data to the data, the Abell 370 elliptical galaxies are significantly bluer in the redshifted elliptical template of Kinney et al. (1996) to the data. The UHT spectra to create UV spectra that extend across the entire 3700 Å. Both bandpasses are truncated at 1989) in the optical (3200–6200 Å). We spliced the spectrum falls off the edge of the FOC detector, and thus the data are not useful as another check on the absolute calibration.

4. COMPARISON TO LOCAL ELLIPTICAL GALAXIES

Translating our F130LP/F370LP ratio to cannot be done in a model-independent manner, so we compare our measurements to nonevolving templates of elliptical galaxies and then discuss the effects of evolution. To create our templates, we folded the spectra of three nearby well-studied elliptical galaxies (M49, M60, and NGC 1399) through the FOC instrument response function using the IRAF/STSDAS routine CALCPHOT. The galaxies were observed by HUT in the far-UV (900–1840 Å), by IUE in the near-UV (1240–3200 Å), and by the 4000 Å break project (Kimble, Davidsen, & Sandage 1989) in the optical (3200–6200 Å). We spliced the IUE and HUT spectra to create UV spectra that extend across the entire UV range, keeping the HUT data in the region of overlap. The optical data were then extended to 9900 Å by normalizing the redshifted elliptical template of Kinney et al. (1996) to the data in the 5000–6200 Å region. Because the optical and UV data do not overlap, we spliced them together at 3200 Å after normalizing each to the flux levels given by Burstein et al. (1988). These templates thus reproduce the flux and in the cores of these galaxies, as viewed from distances of 21.9, 21.9, and 24 Mpc for M49, M60, and NGC 1399. We then redshifted our templates to z = 0.375, applying no corrections for evolution. The three spectra serve as nonevolving templates for comparison to Abell 370.

The predicted FOC count rates for our templates are shown in Table 2; we use them to construct a relation between and F130LP/F370LP and then interpolate the approximate color for each of our Abell 370 elliptical galaxies. These elliptical galaxies appear at moderate UV upturn strength; in the large 65 pixel aperture, two are similar to M49, and two fall between M49 and M60. Note that F130LP/F370LP would be 1.11 if M49 produced no flux shortward of rest-frame 2500 Å, and so all of our Abell 370 measurements are significant detections of UV emission. Uncertainties from counting statistics are less than 1%. From tests measuring the galaxy fluxes in the individual frames, with the background level artificially varied by ±1%, we estimate that the systematic errors can be no more than about 10%. With the exception of BOW 24b, the Abell 370 elliptical galaxies are significantly bluer in smaller aperture. Most nearby elliptical galaxies (including M49, M60, and NGC 1399) also become bluer in smaller radii (Ohl et al. 1998), hence the relevance of comparison between equivalent apertures. Some flux from the main-sequence turnoff is present shortward of rest-frame 2700 Å. Main-sequence turnoff evolution thus has some effect on the F130LP/F370LP ratio, but the effect is small for a lookback time of 4 Gyr. The massive elliptical galaxy model of Tantalo et al. (1996) serves as an example. Without UV upturn stars, a 5 Gyr population has F130LP/F370LP = 1.17, and a 10 Gyr population has F130LP/F370LP = 1.12 (i.e., a 4% effect); with a UV upturn present, the effect is even smaller.

5. DISCUSSION

Because they are composed of old, passively evolving populations, elliptical galaxies offer great promise for tracing the evolution of the universe. One of the major goals in extragalactic research is the determination of the “redshift of formation” z, that marks the age at which most of the stars in early-type galaxies formed. The formation redshift is a parameter that may have less meaning in a universe in which elliptical galaxies are formed through hierarchical merging, but recent studies of galaxy clusters at optical and infrared wavelengths, out to z ~ 1 and including Abell 370, are consistent with the monolithic collapse of massive cluster galaxies at high redshift (z ~ 2–4) followed by quiescent evolution thereafter (Stanford, Eisenhardt, & Dickinson 1998; Kodama et al. 1998). These studies also demonstrate that early-type galaxies in cluster cores show no evidence of recent star formation, although there may be some indication for recent star formation in the galaxies lying on the cluster outskirts (Stanford et al. 1998 and references therein).

The UV upturn provides a sensitive tracer of age in old populations and can potentially constrain z with an independent diagnostic, tracing the hotter populations at shorter wavelengths. Our observations of elliptical galaxies in Abell 370 show no evidence for evolution to a lookback time of approximately 4 Gyr. With only four galaxies at one redshift, it is premature to make detailed comparisons to models. Nevertheless, it is interesting to consider the implications of the Abell 370 measurements for the redshift of formation of cluster elliptical galaxies (if the models are valid) and to compare the detections qualitatively to the expectations from the models.

Figure 1 shows the evolution of the UV upturn as measured by our F130LP/F370LP ratio (assuming the bandpasses are blue shifted with respect to the model spectra by 1.375). In our assumed cosmology, the current age of the universe is 13 Gyr, and the Abell 370 elliptical galaxies are observed in a universe of age 9 Gyr. We assume three formation redshifts; z = 2, 4, and 8. In this example, we again use the infall models of Tantalo et al. (1996). The Tantalo et al. (1996) models assume that galaxies evolve with infall of primordial gas and include the effects of galactic winds. In their most massive models (1–3 × 10^12 M_☉), the UV upturn “turns on” at a galactic age of 6 Gyr (with the ascension of metal-rich EHB and post-EHB stars), reaches the strength seen in local galaxies by an age of 7 Gyr, and levels off thereafter (see Tantalo et al. 1996, Fig. 16).

Given that the F130LP/F370LP ratio ranges from 1.23 to 1.34 in these four Abell 370 elliptical galaxies, we can infer that they formed at a redshift of at least 4, assuming the model assumptions are valid. Models of lower mass (0.1–5 × 10^11 M_☉) do not reach our observed range of UV upturn strength before 15 Gyr and thus are not included in Figure 1. Measurements of the UV upturn for less luminous elliptical galaxies at this redshift would be of great interest. If the Abell 370 elliptical galaxies and the local population of elliptical galaxies both formed at a common redshift of z ≥ 4, the lack of evolution seen in the UV upturn can be understood as evidence that both epochs are on the “flat” portion of the UV upturn evolutionary curves, after the UV upturn has leveled off.
U V upturn is delayed until 10 G yr. The elliptical galaxies in the integrated colors in these more recent models is that in the timescale. The main discrepancy between our observations and winds, the efficiency of the star formation rate, and the accretion scheme, and several parameters could be tuned to give agreement with our results, such as the time of onset for galactic winds, the efficiency of the star formation rate, and the accretion timescale. The main discrepancy between our observations and the integrated colors in these more recent models is that in the most massive (and rapidly evolving) models, the rise of the U V upturn is delayed until 10 Gyr. The elliptical galaxies in Abell 370, observed in a universe of age 9 Gyr, would not have the time to achieve their measured U V colors even if they were formed at very large $z_f$.

A different discrepancy occurs when we compare our data to the theoretical predictions of Yi et al. (1998). In their models, the U V upturn can appear at ages as early as 5 Gyr and as late as 10 Gyr, but the $m_{550} - V$ color increases continuously from 6 to 0 mag. Today's local elliptical galaxies thus lie along a steep slope in the Yi et al. (1998) scheme and should fade very rapidly with lookback time under all five sets of their models. Our results are thus strongly inconsistent with the Yi et al. (1998) predictions.

One way around the rather surprising result that the U V upturn exists at $z = 0.375$ is to imagine that the U V emission we are seeing comes from star formation. The galaxies selected for our study are among the best studied at this redshift and show no morphological, spectroscopic, or optical photometric evidence of star formation. Nevertheless, a star formation rate of approximately only 0.02 $M_\odot$ yr$^{-1}$ would be enough to produce the U V upturn we observe (see Madau, Pozzetti, & Dickinson 1998). In this case, the hypothesis would be that elliptical galaxies are still forming stars at a low level at $z = 0.375$ but must cease to do so by $z = 0$. UV observations of clusters at intermediate redshifts will test whether this is correct.

Our measurements provide a first step in mapping the evolution of the U V upturn with lookback time. Further observations are clearly needed to rule out star formation as the source of the U V emission in these high-redshift galaxies and to trace the evolution to both higher and lower redshifts. HST observations of a cluster at $z = 0.55$ are planned in the near future (Guaranteed Time Observer proposal 8020). Unless the redshift of formation is very high, these galaxies ought to be very faint in the far-U V.

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