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CONSTRAINTS ON THE ORIGIN OF THE ULTRAVIOLET UPTURN IN ELLIPTICAL GALAXIES FROM HOPKINS ULTRAVIOLET TELESCOPE OBSERVATIONS OF NGC 1399

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ABSTRACT

The giant elliptical galaxy NGC 1399 was observed with the Hopkins Ultraviolet Telescope (HUT) aboard the Astro-1 space shuttle mission in 1990 December. These are the first data to provide measurements of the spectral energy distribution of an elliptical galaxy shortward of Lyα and to allow detection of absorption features in the sub 2000 Å UV. The spectrum shows no emission features other than well-known geocoronal lines. Strong Lyman series absorption is evident at the galaxy redshift. Other absorption features attributable to the hot stellar population are detected, but there is no evidence of C IV λλ1548, 1551 absorption.

We use these data to set constraints on the origin of the UV upturn in elliptical galaxies. The lack of detectable C IV absorption and the shape of the continuum spectrum exclude star formation with a standard IMF as the *sole* contributor to the 1550 Å flux. The spectral energy distributions predicted by the "hot-E" model of Guiderdoni and Rocca-Volmerange and the Bruzual μ-models do not match the observed spectrum. Post-asymptotic giant branch (PAGB) stars can account for the spectrum near 1550 Å, because many have low carbon abundance in their envelopes. However, synthetic spectra produced from theoretical evolutionary tracks and stellar model atmospheres fail to fit to the observed spectral-energy distribution. If PAGB stars produce the UV upturn, then either they do not evolve along the standard tracks, or the (solar metallicity) model atmospheres used to construct the synthetic spectrum are inappropriate. The observed continuum flux decreases from 1050 Å to the Lyman limit, indicating that the light is dominated by stars with temperatures less than 25,000 K. For star-formation models, this temperature puts the main-sequence turnoff near B0, implying either that star formation ended $\sim 2 \times 10^7$ yr ago, or that stars are currently forming with a truncated IMF. The continuum shape and presence of Lyman-series absorption suggest extreme horizontal-branch star models deserve additional attention.

Subject headings: galaxies: individual (NGC 1399) — galaxies: stellar content — ultraviolet: spectra

1. INTRODUCTION

Understanding the spectral evolution of galaxies is one of the key stumbling blocks in determining the cosmological deceleration parameter q_0. The problem is exacerbated by the difficulties in modeling the integrated spectra of nearby *old* stellar populations in elliptical galaxies and spiral bulges. While the optical spectra of these galaxies are well matched by an old metal-rich stellar population, the far-UV flux is poorly understood. UV observations from the *OAO 2*, *IUE*, and *ANS* satellites have shown that these galaxies typically have an upturn in their spectra shortward of 2000 Å, with flux increasing to shorter wavelengths (Code & Welch 1979; Bertola et al. 1980, 1986; Perola & Tarenghi 1980; Bertola, Capaccioli, & Coke 1982; O'Connell, Thuan, & Puschell 1986). The galaxy surface-brightness profiles are similar in the optical and UV (Oke, Bertola, & Capaccioli 1981; Nørgaard-Nielsen & Kjaergaard 1981; Welch 1982; Bohlin et al. 1985), but the strength of the upturn varies from galaxy to galaxy. The ratio of the 1500 Å flux to the optical flux increases with galaxy luminosity and metallicity (Burstein et al. 1988) and may be correlated as well to the mass-infall rate derived from the X-ray luminosity. While emission lines have been reported in the *IUE* spectra of several ellipticals, with the exception of Lyα (Bertola et al. 1986; Buson, Bertola, & Burstein 1990) the detections are of very low significance.

Even the best *IUE* spectra of ellipticals show no strong absorption features, and there is no sign of a turnover in the continuum down to 1200 Å. Nevertheless, the UV upturn is thought to be produced by stars. Possible stellar populations include (1) young hot stars that are part of a minority star-forming population (Gunn, Stryker, & Tinsley 1981; Rocca-Vomerange & Guiderdoni 1987; hereafter RG); (2) post-asymptotic giant-branch (PAGB) stars similar to the central stars of planetary nebulae (Rose & Tinsley 1974;

Mochkovitch 1986; Bohlin et al. 1985; Burstein et al. 1988; Barbaro & Olivi 1989; Brocato et al. 1990); (3) hot horizontal branch (HB) stars, either from the metal-rich population that dominates the optical light, or from a minority metal-poor population (Ciardullo & Demarque 1978; Bruzual 1983; Nesci & Perola 1985; Arimoto & Yoshii 1987); or (4) accreting white dwarfs (Greggio & Renzini 1983; Nesci & Perola 1985; Mochkovitch 1986). These possibilities and variations upon them have recently been reviewed in great detail by Greggio & Renzini (1990).

From its inception in 1978, the Hopkins Ultraviolet Telescope (HUT) project (Davidsen et al. 1991) has had the solution, or at least the illumination, of this problem as one of its primary scientific goals. A fast focal ratio (*f*/2) and large apertures were incorporated in HUT to maximize its capability for measuring the far-UV spectra of giant ellipticals. During the Astro-1 space shuttle mission in 1990 December, we used HUT to obtain long exposures of NGC 1399 and the bulge of M31. In this *Letter*, the continuum shape and absorption features in the spectrum of NGC 1399 are used to set constraints on the origin of the UV upturn. Models with constant star formation are considered in § 3. PAGB star models are considered in § 4. We will not consider HB stars and accreting white dwarfs because of the uncertainties in constructing model spectra for such populations. However, the constraints we place on the other models suggest that these two possibilities should be studied in more detail. Analysis of the M31 spectrum, and more detailed modeling of the NGC 1399 absorption spectrum, will be presented in future papers.

2. OBSERVATIONS

Of the "quiescent" ellipticals analyzed by Burstein et al. (1988), NGC 1399 has the strongest UV upturn. While NGC 1399 is the central galaxy of the Fornax cluster and is surrounded by an X-ray halo (Killeen & Bicknell 1988), it is more than 200 times less luminous than M87 in X-rays, and the mass accretion rate from the putative cooling flow is 1.17 $M_\odot$ yr^{-1} (Burstein et al. 1988).

We observed NGC 1399 with HUT during orbital night for a total of 5440 s. HUT consists of a 0.9 m primary mirror that feeds a prime-focus, Rowland-circle spectrograph with a microchannel-plate intensifier and a one-dimensional Reticon detector. First-order sensitivity covers the region from 850 to 1850 Å at 0.5 Å pixel^{-1} with $\sim$3 Å resolution. Galactic H I absorption acts as a natural blocking filter for second-order radiation below 912 Å. Details of HUT can be found in Davidsen et al. (1991). A 9″ × 116″ aperture was centered on the galaxy nucleus, with the long dimension of the aperture at a position angle of 0°. A star was inadvertently included at one end of the aperture, but far-UV images taken with the Ultraviolet Imaging Telescope (UIT) aboard Astro-1 (O'Connell et al. 1991) show that this is an insignificant contributor to the far-UV flux. The raw spectrum, binned over 1.5 Å, is shown in Figure 1. All significant emission lines are due to airglow from the residual atmosphere above the shuttle. Scattered Lyα affects the shape of the spectrum between $\sim$1160 and 1270 Å. The strengths of the airglow features vary with the shuttle's orbital position and orientation, and detailed models will be required before they can be subtracted effectively. As a first attempt, we constrained the shapes of the airglow lines by fitting the line profiles in a separate airglow observation taken through the 9″ × 116″ aperture during orbital night. We then fixed the line profiles, and found the best fit of a continuum + airglow model to the regions around the individual lines in the NGC 1399 spectrum. For Lyγ, Lyβ, second-order He I λ584 and O I λ1304, the fit was made avoiding the regions possibly contaminated by strong absorption lines in NGC 1399. The line profile fits match the broad scattering wings quite well, but are not particularly satisfactory near the peaks of the strong Lyα and O I λ1304 lines, where deadtime corrections are important; therefore for the spectral fitting discussed below, we have excluded the region from 1194–1225 Å and from 1300–1308 Å. The mean backgound was determined from the count rate between 844 and 893 Å (a region free from airglow and emission from NGC 1399) and was also subtracted from the NGC 1399 spectrum. No correction for galactic extinction has been applied, because the measured extinction in the direction of NGC 1399 is zero to within the errors of existing measurements (Burstein & Heiles 1984). Counts were converted to flux using the HUT absolute calibration based on a model atmosphere of the white dwarf G191-B2B (Davidsen et al. 1991). The observed spectral energy distribution is similar to that seen with *IUE* (see Fig. 2). A preliminary examination of the pointing errors suggests that the HUT fluxes should be corrected upward by $\sim$10% to account for the time the galaxy was not centered in the slit. Nevertheless, integration of the NGC 1399 optical profile (Franx, Illingworth, & Heckman 1989) over the areas of the HUT and *IUE* slits gives a HUT/*IUE* flux ratio of 1.4 if the UV profile follows the optical profile. The observed mean ratio is $\sim$1.1 (using the above estimate of the pointing-error correction), suggesting that the far-UV light is more concentrated toward the center of the galaxy, in accordance with the UIT findings (O'Connell et al. 1991).

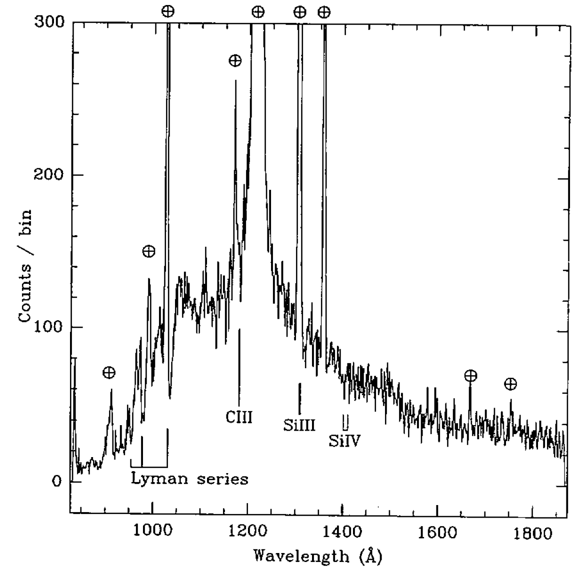

FIG. 1.—The observed HUT spectrum of NGC 1399, binned over 1.5 Å, uncorrected for airglow. The wavelengths of the marked absorption features are consistent with the redshift of NGC 1399. The broad absorption features between 1000 and 1150 Å are undoubtedly blends of many features, as *Copernicus* spectra of hot stars show several lines per angstrom in this wavelength range (Snow & Jenkins 1977). Airglow features are indicated with the ⊕ symbol.

3. CONSTRAINTS ON YOUNG STARS

While the evidence is already quite strong that young stars cannot be causing the UV upturn in the bulge of M31 (Welch

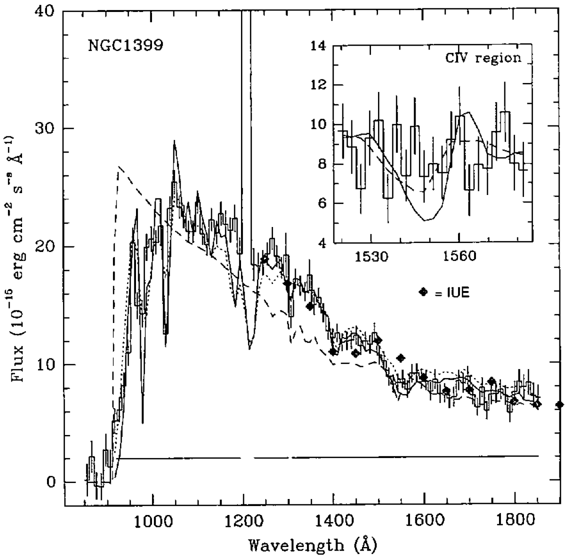

FIG. 2.—Comparison of NGC 1399 spectrum near 1550 Å with models. The histogram in the main figure is the flux-calibrated HUT spectrum, binned at 10 Å intervals. Error bars were computed from counting statistics on the raw NGC 1399 spectrum and the standard deviation in the dark count rate. *IUE* fluxes from Burstein et al. (1988) are shown as diamonds. The solid line shows the best-fitting solar-metallicity Kurucz (1991) model atmosphere. The model parameters are $T_{\rm eff} = 24{,}000$ K, and log $(g) = 4.0$. Regions used in the fit are indicated by the horizontal line at the bottom of the plot; regions contaminated by strong airglow lines were excluded. While the model spectrum looks qualitatively similar to NGC 1399, all single-temperature, solar-metallicity models are formally excluded (best fit $\chi^2/\nu = 4.4$ with 86 degrees of freedom). The dashed line shows the RG hot-E model at an age of 13 Gyr; the reduced χ^2 for this model is 20.9. The dotted line shows a model of constant star formation over 10^9 yr with an IMF slope of $x = -0.1$ and an upper mass cutoff of $M_{\rm upper} = 20\ M_\odot$. The reduced χ^2 for this model is 4.3. The inset shows a comparison of the observed C IV profile to that expected from a population of young stars. The histogram shows the data. The solid line is for a Salpeter IMF from 0.85 to 119 $M_\odot$ forming at a constant rate over 10^8 yr. The dashed line is the RG hot-E model (IMF slope $x = 1.7$ with an upper mass limit of 80 $M_\odot$; exponentially declining SFR with time scale $\tau = 2.7$ Gyr). The best fit to the data is a featureless continuum (modeled by a blackbody), which gives $\chi^2 = 19.6$ with 19 degrees of freedom. The hot-E model gives $\chi^2 = 26.2$, and so is excluded with 95% confidence. The solid line is an even poorer fit, with $\chi^2 = 45.3$.

1982; Bohlin et al. 1985), young stars are not excluded by the *IUE* observations of ellipticals. Continuing star formation was proposed as the source of the UV upturn by Bruzual (1983) in his "μ-models," and more recently by RG in their "hot-E" model, and by Bica & Alloin (1988) on the basis of spectral synthesis using globular cluster templates.

The most distinctive feature in the *IUE* spectra of normal O stars is strong C IV absorption at $\lambda\lambda$1548, 1551. In supergiants, this blend can have an equivalent width of up to 20 Å, and usually exhibits a strong P Cygni profile. In main-sequence O stars with normal atmospheric C abundance, the equivalent width ranges from ~12 Å for O4V stars to ~3 Å for O9V stars (Walborn, Nichols-Bohlin, & Panek 1985). Equivalent widths even at the low end of this range would be detectable in the HUT spectrum.

To set limits on the amount of present-day star formation, we have constructed synthetic spectra using an "isochrone synthesis" technique similar to that of Charlot & Bruzual (1990). Evolutionary tracks for high-mass stars from Maeder & Meynet (1988, hereafter MM) were used, with bolometric corrections taken from Humphreys & McElroy (1984) and Flower (1977). Isochrones were constructed using an iterative interpolation scheme between the "physically distinct" points identified by MM along the tracks. The interpolation scheme ensures that there are no large discontinuities along a given isochrone by successively reducing the mass step until the change in L and $T_{\rm eff}$ is smaller than a set tolerance (0.1 dex). For setting constraints from the C IV line, synthetic spectra were constructed using the ESA *IUE* spectral atlas (Heck et al. 1984). Where possible, stars with small values of $E(B-V)$ were chosen and were corrected for extinction using the curve from Savage & Mathis (1979). Because we are considering only a small region around C IV, uncertainties in the extinction correction should have little effect. Our purpose here is to test whether young stars *alone* can be responsible for the UV upturn; therefore, no evolved stars are considered in these models. When the stars reach the end of the MM tracks, they simply disappear.

Most of the flux in the HUT bandpass comes from stars with main-sequence lifetimes that are less than a few times 10^7 yr; therefore the details of the star-formation history are unimportant as long as the star-formation rate is relatively constant over this short time scale. Figure 2 (inset) shows the region around C IV, binned to a resolution of 3 Å, compared to the C IV profile expected from a population of stars forming at a constant rate over 10^8 yr with a Salpeter IMF from 0.85 $M_\odot$ to 119 $M_\odot$. This model is excluded at the 99.9% confidence level by a χ^2 comparison to the data. A 2 σ upper limit is that stars from this model can be responsible for no more than 50% of the 1550 Å flux (less if the component producing the rest of the light also has intrinsic C IV absorption). The RG hot-E model is constructed at 10 Å resolution, so the C IV line is less well resolved. Nonetheless, direct comparision of the 13 Gyr hot-E model to the HUT spectrum at C IV indicates that it is excluded at the 95% confidence level.

Additional constraints on the temperatures of the stars producing the UV upturn can be derived from the continuum shape over the entire HUT bandpass. Comparison to the Kurucz (1991) solar-metallicity models excludes stars hotter than ~25,000 K as significant contributors to the UV upturn. Hotter stars produce too much flux below 1050 Å. The best-fit model is shown as a solid line in Figure 2. Of course, this temperature limit may be sensitive to the amount of line blanketing shortward of 1100 Å, which is presumably higher for the metal-rich stars thought to inhabit NGC 1399. Nevertheless, the best-fit temperature (24,000 K) is consistent with the absence of C IV absorption; stars hotter than ~28,000 K would probably have detectable C IV, especially if they are metal rich. Even at the temperature inferred from the continuum fitting, the Si IV $\lambda\lambda$1394, 1403 and C III λ1175 lines in NGC 1399 seem unusually weak (compared to *Copernicus* spectra of stars of similar temperature), suggesting that the dominant population in the far-UV *may not* be metal rich. Detailed analysis of the absorption-line spectrum is currently in progress.

The turnover in the continuum limits the number of massive stars that can be evolving at present along the main sequence in NGC 1399. The dashed line in Figure 2 shows that the RG hot-E model far overshoots the continuum below 1000 Å. Similar difficulties are encountered with the Bruzual μ-model, as his assumed IMF was similar to RG's. A lower upper mass cutoff and flatter IMF slope are required to fit the HUT spectrum. The best-fit constant-star-formation model (shown as a dotted line in Fig. 2) has $M_{\rm upper} = 20\ M_\odot$ and an IMF slope $x = -0.1$. Imposing such a sharp upper-mass cutoff on an

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IMF that is weighted toward massive stars seems implausible. Furthermore, the star-formation rate inferred from this IMF (with $M_{\rm lower} = 0.1\ M_\odot$) is less than 1% of the estimated mass-inflow rate from the X-ray gas. To get a higher star-formation rate (and simultaneously provide the UV flux) requires a rather contrived IMF, steeply rising toward low masses for stars less massive than $\sim 2\ M_\odot$, but flat or rising toward high masses for more massive stars.

Because the limits on temperature come primarily from the observed turnover in the spectrum below 1050 Å, the strength of these conclusions is tempered by several uncertainties. First, our fits to the spectrum depend on the correctness of the Bergeron (1990; private communication) DA white dwarf model atmosphere (used to determine the HUT sensitivity) and the Kurucz (1991) LTE model atmospheres, neither of which have been extensively tested in the sub-Lyα UV. Work is currently in progress to use other HUT spectra to set constraints on the model atmospheres; nonetheless, the agreement with the preflight laboratory calibration and comparison between white-dwarf spectra suggest that calibration uncertainties are too small to affect significantly the turnover in the NGC 1399 spectrum.

The second uncertainty is that the shape of the interstellar extinction curve is poorly known below Lyα. While extinction due to the Milky Way along the line of sight to NGC 1399 appears to be small, observations with the Broad-Band X-Ray Telescope (BBXRT) aboard Astro-1 suggest that a column density $N_{\rm H}$ a few times 10^{21} cm^{-2} is required to fit the X-ray spectrum (Loewenstein 1991). Such absorption, if due to cold gas combined with dust in the galactic dust-to-gas ratio, would produce an extinction of more than 2.5 mag at 1000 Å. However, NGC 1399 has normal optical colors and shows no morphological evidence for dust (Sadler & Gerhard 1985), suggesting that little dust is present in the X-ray absorbing gas. Furthermore, studies of the galactic extinction curve (Longo et al. 1989) suggest that dust is unlikely to produce the sharp turnover seen near the Lyman limit in the NGC 1399 spectrum.

4. CONSTRAINTS ON PAGB STARS

The constraints on the temperature cause difficulties for PAGB models of the UV upturn. Stars on the PAGB typically spend a significant fraction of their time at temperatures in excess of 50,000 K, prior to cooling and fading onto the white dwarf sequence. To test the PAGB hypothesis, we constructed synthetic spectra of single-mass populations of stars evolving along the tracks given by Schönberner (1987). Solar-metallicity model atmospheres from Kurucz (1991) and Clegg & Middlemass (1987) were used to build the spectrum in the HUT bandpass. The resulting best-fit models are shown in Figure 3. The model spectra are relatively insensitive to the assumed mass of the PAGB star because most of the stars are so hot that their spectra turn over shortward of the Lyman limit. All of the models significantly overshoot the observed continuum below ∼980 Å. It is unlikely that problems with airglow subtraction could explain the discrepancy. First, the Lyα airglow line is too narrow to explain the broad excess in flux of the data over the models between 1350 and 1100 Å. Also, the agreement of the HUT and *IUE* data is good between 1350 and 1250 Å, where airglow subtraction might be expected to cause problems. Second, there is negligible airglow contamination between 970 and 920 Å, where the disagreement with the models is most significant. Extinction is also unlikely to explain the discrepancy, for the reasons stated at the end of § 3. If PAGB stars produce the UV upturn, then either they do not evolve along the Schönberner tracks, or the model atmospheres used to construct the synthetic spectrum are inappropriate. Once again, the lack of detectable C IV bolsters our confidence in the constraints derived from continuum fitting; high-temperature, metal-rich PAGB stars with enough of an envelope left to produce the observed Lyman lines and C III λ1175 would probably produce detectable C IV. The most consistent interpretation of the data is that cooler stars are responsible for the UV upturn in this galaxy.

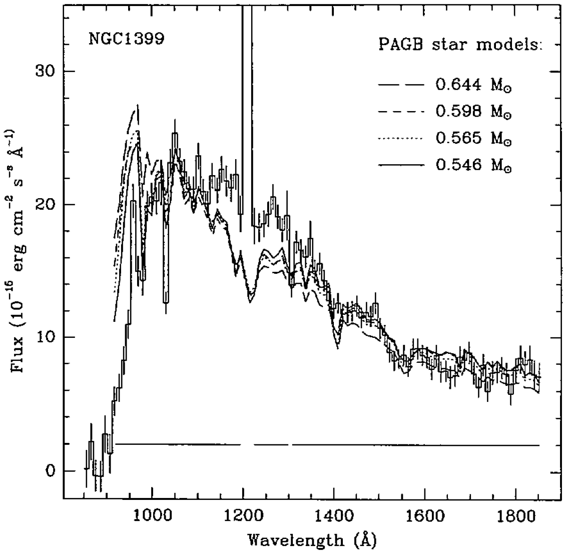

FIG. 3.—NGC 1399 spectrum compared to the spectra expected from single-mass populations of PAGB stars. Four models are shown for the different evolutionary tracks of Schönberner (1987). Synthetic spectra were constructed by summing Kurucz (1991) and Clegg-Middlemass (Clegg & Middlemass 1987) model atmospheres, weighted by the time spent and the luminosity at each of the points marked on Schönberner's (1987) Fig. 2. The results are not significantly different if only the Kurucz models are used. The best fit to the data is for the 0.546 $M_\odot$ model, with a reduced $\chi^2 = 8.26$.

5. CONCLUSIONS

The HUT spectrum of NGC 1399 from 1850 Å to the Lyman limit sets new constraints on the source of the UV upturn in elliptical galaxies. Young stars appear unable to match either the shape of the continuum or the lack of C IV absorption, unless they are forming with an unusual IMF or formed in a burst that ended $\sim 2 \times 10^7$ yr ago, such that B0 stars define the main-sequence turnoff. Synthetic spectra of simple PAGB star populations also fail to match the observed continuum shape. A maximum temperature of $T_{\rm eff} \sim 25{,}000$ K is inferred from comparison to solar-metallicity Kurucz models, suggesting that perhaps HB models merit more detailed consideration. The absorption spectrum below Lyα contains much more information than we have exploited in this *Letter*, providing additional constraints on the UV stellar population (Ferguson et al. 1992).

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