PHOTOSPHERIC ABUNDANCES OF THE HOT STARS IN NGC 1399 AND LIMITS ON THE FORNAX CLUSTER COOLING FLOW

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ABSTRACT

We present far-UV spectroscopy of the giant elliptical galaxy NGC 1399, obtained with the Far Ultraviolet Spectroscopic Explorer. Of all quiescent ellipticals, NGC 1399 has the strongest known "UV upturn" – a sharp spectral rise shortward of 2500 Å. It is now well-established that this emission comes from hot horizontal branch (HB) stars and their progeny; however, the chemical composition of these stars has been the subject of a long-standing debate. For the first time in observations of any elliptical galaxy, our spectra clearly show photospheric metallic absorption lines within the UV upturn. The abundance of N is at 45% solar, Si is at 13% solar, and C is at 2% solar. Such abundance anomalies are a natural consequence of gravitational diffusion. These photospheric abundances fall in the range observed for subdwarf B stars of the Galactic field.

Although NGC 1399 is at the center of the Fornax cluster, we find no evidence for O VI cooling flow emission. The upper limit to $\lambda\lambda 1032,1038$ emission is 3.9×10^{-15} erg s^{-1} cm^{-2}, equivalent to 0.14 $M_\odot$ yr^{-1}, and less than that predicted by simple cooling flow models of the NGC 1399 X-ray luminosity.

Subject headings: galaxies: abundances – galaxies: elliptical – galaxies: stellar content – ultraviolet: galaxies

1. INTRODUCTION

The spectra of elliptical galaxies and spiral galaxy bulges exhibit a strong upturn shortward of 2700 Å, dubbed the "UV upturn." The phenomenon was among the first major discoveries in UV extragalactic astronomy (Code 1969), and the implied existence of a hot stellar component in ellipticals contradicted the traditional picture of early-type galaxies as old, cool, passively-evolving populations. Early debate covered many possible candidates for the UV upturn origin (see O'Connell 1999), but today we know from UV spectroscopy (Ferguson et al. 1991; Brown et al. 1997) and imaging (Brown et al. 2000) that this UV emission comes from a minority population of extreme horizontal branch (EHB) stars and their progeny. These stars appear to be analogs of the subdwarf B (sdB) and O (sdO) stars of the local Galactic field, but the populations may differ considerably in the two cases.

The UV upturn is not completely understood, however. Long before the observational proof of an EHB origin, EHB stars were a strong theoretical candidate, and there have been two schools of thought regarding their nature. One possibility is that the EHB stars reside in the metal-poor tail of a wide metallicity distribution (e.g., Park & Lee 1997). Another possibility is that the EHB stars lie at high metallicity, reflecting the composition found in the cooler, dominant populations of elliptical galaxies (e.g., Brocato et al. 1990; Bressan, Chiosi, & Fagotto 1994; Greggio & Renzini 1990; Dorman, O'Connell, & Rood 1995; Horch, Demarque, & Pinsonneault 1992; Brown et al. 1997). The metallicity controversy is tied to the "second parameter" debate, which seeks to understand the role of parameters (besides metallicity) that govern HB morphology in globular clusters; possible candidates include age, mass loss, He abundance, rotation, and cluster dynamics (see Fusi Pecci & Bellazzini 1997).

Characterized by the $m_{1550} - V$ color, the UV upturn shows surprisingly strong variation (ranging from 2.05–4.50 mag) in nearby quiescent early-type galaxies (Bertola, Capaccioli, & Oke 1982; Burstein et al. 1988), even though the spectra of ellipticals at longer wavelengths are qualitatively very similar. The $m_{1550} - V$ color is positively correlated with the strength of Mg_2 line absorption in the V band (i.e., bluer at higher line strengths), opposite to the behavior of optical color indices (Burstein et al. 1988). Both sides in the EHB metallicity debate see this correlation as further proof of their own scenario. The metal-poor school reasons that galaxies with strong UV emission are more massive and formed earlier; such galaxies have higher *mean* metallicity, as tracked through optical indices, even though the upturn comes from stars in the metal-poor tail. In this scenario, age is the dominant "second parameter" driving HB morphology, with the metal-poor HB becoming more blue with age, thus producing more UV emission in massive old galaxies. In contrast, the metal-rich school argues that the trend for the HB distribution to become redder at increasing metallicity can be reversed at high metallicity, due to increased He abundance and possibly a higher mass-loss rate on the red giant branch (RGB), both of which lead to more metal-rich EHB stars and a subsequent increase in UV emission from the population. These hypotheses imply different ages for the stellar populations in these galaxies. Ages exceeding those of Galactic globular clusters are required under the metal-poor Park & Lee (1997) hypothesis, while ages as low as 8 Gyr are allowed in the metal-rich Bressan et al. (1994) model.

With this debate in mind, we obtained observations of NGC 1399 with the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000). NGC 1399 is the giant elliptical galaxy at the center of the Fornax cluster. It has the strongest

UV upturn of any quiescent elliptical galaxy measured to date ($m_{1550} - V = 2.05$ mag; Burstein et al. 1988). Although the UV upturn correlates well with optical metallicity indices, such indices track the composition of the cool population (RGB and main sequence stars). Our far-UV spectroscopy is intended to measure the photospheric abundances in the hot stars producing the UV upturn – measurements not possible in earlier spectroscopy of elliptical galaxies (Brown et al. 1997; Ferguson et al. 1991), due to the low signal-to-noise and resolution. In addition, X-ray observations suggest NGC 1399 is the host to a significant cooling flow (Bertin & Toniazzo 1995; Rangarajan et al. 1995), making it an interesting target for O VI emission measurements. We present here an analysis of our FUSE data for NGC 1399; future papers will present our observations of other ellipticals, which are not yet complete.

2. OBSERVATIONS

We observed NGC 1399 on 12–13 Dec 2000 and 3 Oct 2001 for 28 ksec, with 20 ksec during orbital night. The spectroscopic resolution is limited by the velocity dispersion of the galaxy (331 km s^{-1}; Burstein et al. 1988), so we scheduled observations in the default $30'' \times 30''$ low-resolution square aperture. The data were obtained in time-tag mode, recording the arrival time and detector position of each photon.

We reprocessed the data using the CALFUSE software, version 2.0.5. Scattered light and airglow emission lines both increase during orbital day, so we rejected daytime data. We also implemented pulse-height screening appropriate for very faint targets, by raising the minimum pulse height in CALFUSE from 0 to 4, thus discarding more of the detector dark counts with little loss of source counts.

Useful data were obtained in all detector segments, each with its own wavelength bins and instrumental resolution. Because the velocity dispersion limits the useful resolution, we coadded all of the data onto a linear wavelength scale (0.25 Å bins), with propagation of statistical errors. The bins in our coadded data are much larger than the nominal FUSE wavelength bins (~ 0.01 Å), but they adequately sample the resolution elements in the spectrum (> 1 Å for velocity-broadened features). We masked bad pixels when coadding the data, because CALFUSE does not account for small-scale flat-field features. Note that the wavelength solution in this version of CALFUSE is improved significantly, although these corrections are unimportant in our large wavelength bins. Furthermore, although fixed pattern noise can be an issue in high-resolution FUSE data, it is negligible for our large bins and coadded detector segments.

3. STELLAR MODELS

Our FUSE spectra offer the first clear detection of metallic absorption lines from the hot stars responsible for the UV upturn. Previously, Brown et al. (1997) fit composite models to the spectra of elliptical galaxies observed with the Hopkins Ultraviolet Telescope (HUT), including NGC 1399. Those spectra were obtained through large apertures, with coverage from 900–1800 Å, but the low signal-to-noise and resolution hampered detection of individual absorption lines from elements heavier than H. Brown et al. (1997) integrated synthetic spectra over EHB evolutionary tracks from Dorman, Rood, & O'Connell (1993), using synthetic spectra appropriate for the HUT resolution (Brown, Ferguson, & Davidsen 1996). The models reproduce well the entire far-UV spectral energy distribution, and show that the light from elliptical galaxies is dominated by a population of EHB stars and their post-HB progeny, the AGB-Manqué stars (Brown et al. 1997).

To analyze the FUSE spectra of NGC 1399, we integrated the best-fitting EHB model from Brown et al. (1997), using new high-resolution synthetic spectra calculated at representative points along the EHB evolutionary path. The track assumes a small HB envelope mass (0.016 $M_{\odot}$), high metallicity ([Fe/H]=0.71), and high main-sequence He abundance ($Y = 0.45$). Note that approximately half of the far-UV flux in this track comes from the EHB itself, with the rest coming from the AGB-Manqué phase. We computed solar abundance atmospheres using the ATLAS9 code (Kurucz 1993), under the assumption of local thermodynamic equilibrium (LTE). Synthetic spectra were then calculated using the SYNSPEC code (Hubeny, Lanz, & Jeffery 1994), again assuming LTE, but with varying abundances of C, N, Si, Fe, and Ni (holding other elements at solar abundance). Note that this code has been used previously to model FUSE and HUT data of sdB stars (Ohl, Chayer, & Moos 2000; Brown et al. 1996). We used the Kurucz (1993) line list in our spectral synthesis, including lines predicted from atomic physics but not yet measured in the laboratory. Weak lines that are experimentally unconfirmed are potentially prone to position and wavelength errors, but they provide the necessary pseudocontinuum.

No Galactic foreground reddening is applied to the models. Both the maps of Burstein & Heiles (1984) and Schlegel, Finkbeiner, & Davis (1998) suggest that $E(B-V)$ is nearly 0 mag along a line of sight toward NGC 1399.

To compare the composite models to the FUSE data, we defined spectral indices of C, N, and Si (Table 1). Each index measures the ratio of the mean flux in a line region to that in continuum regions, selected to be free of strong features from other elements. The C and Si indices come from the ratio in one section of the spectrum, whereas the N index comes from the average in two sections.

TABLE 1: Composition Indices

Ion	Cont. (Å)	Line (Å)	Dominant Transitions (Å)
C III	1170–1173	1174–1177	1174.93 1175.26 1175.59
	1177–1180		1175.71 1175.99 1176.37
N III	986–988	989–993	989.80 991.51 991.58
	994–996		
N II	1074–1078	1083–1087	1083.99 1084.56 1084.58
	1092–1096		1085.53 1085.55 1085.70
Si III	1105–1107	1107–1114	1108.36 1109.94 1109.97
	1114–1116		1113.17 1113.20 1113.23

4. RESULTS

4.1. *Photospheric Abundances*

By varying the abundances in the synthetic spectra, we find that the composition that best reproduces the line indices measured in the data is C at 0.02 ± 0.01 solar, N at 0.45 ± 0.15 solar, and Si at 0.13 ± 0.06 solar (Figure 1). The errors represent statistical uncertainties in each line index, transformed to abundance uncertainties. This result does not significantly depend upon our chosen evolutionary track; although the best-fitting track from Brown et al. (1997) has enhanced He and metallicity, our derived abundances remain unchanged (within 1σ) if we use other unenhanced tracks that reproduce the far-UV spectrum.

Fe and Ni lines blanket the entire FUSE region, but

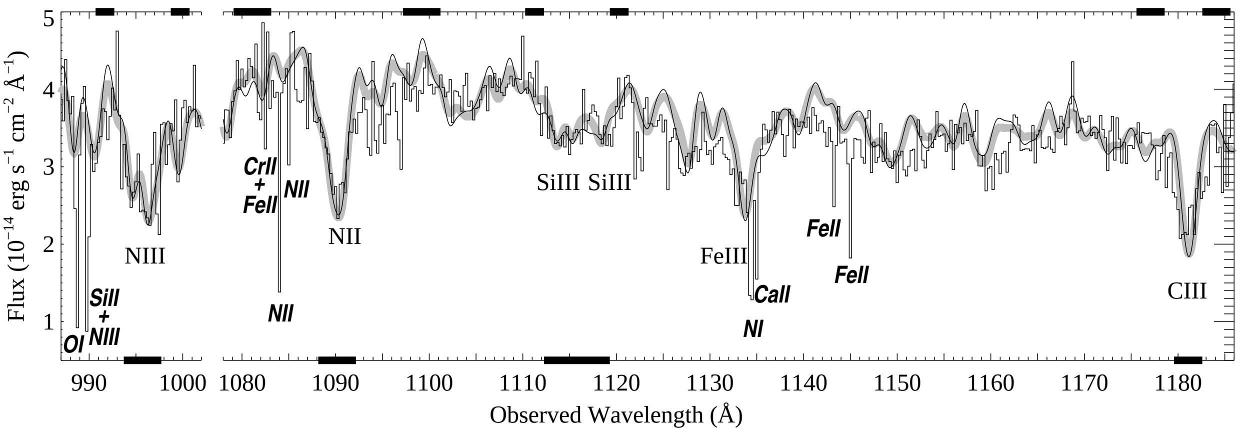

FIG. 1– Sections of the FUSE NGC 1399 spectrum (black histogram). Photospheric (roman) and Galactic ISM (italics) features are easily distinguished by their widths. The composite model is shown with photospheric Fe and Ni at solar (thick grey curve) and 5 times solar (thin curve) abundance. Thick black lines at the top and bottom of the plot denote the regions used for spectral indices (Table 1). The model normalization changes by 10% at the break (the absolute flux calibration varies by $\sim$10% between detector segments).

do not significantly affect the derived abundances of the light elements. To demonstrate the systematic errors from Fe and Ni assumptions, we varied the abundances of Fe and Ni over a extremely large range: from 0.01 solar to 5.0 solar. Throughout this range, the derived abundances of C, N, and Si remain within their 1σ statistical uncertainties. We show the same evolutionary model, when Fe and Ni are enhanced, in Figure 1; the increased Fe and Ni severely depressed the continuum, so the curve has been renormalized upward. Note that diffusion processes tend to deplete the photospheric abundances of the light elements in sdB stars (Lamontagne et al. 1985; Lamontagne, Wesemael, & Fontaine 1987), but Fe can be radiatively supported; e.g., Fe enhancement is thought to be the mechanism for the pulsating sdB stars (Charpinet et al. 1997), which show no photospheric Fe depletion (Heber, Reid, & Werner 2000).

The C and Si line indices rely upon lines that are not resonance transitions, and thus should not be contaminated from any interstellar medium (ISM) in NGC 1399 – i.e., the features in the FUSE spectrum should be completely photospheric. In contrast, the N index comes from series of resonance lines. Because the NGC 1399 spectrum is redshifted by 1424 km s^{-1}, narrow absorption features from these same transitions in the Galactic ISM can be seen in the FUSE spectrum, offset by $\sim$ 5 Å to the blue. If NGC 1399 has a significant cold ISM, the redshifted N features could have both ISM and photospheric contributions.

However, when looking at purely interstellar features in the FUSE data, we see no evidence for absorption from a cold ISM in NGC 1399. The N II and N III features in Table 1 can arise from both hot stellar photospheres and the ISM, but other resonance transitions will arise only from an ISM. These can be used to discern how much contamination of photospheric features we should expect from an ISM in NGC 1399. E.g., strong absorption from N I (1134.2 Å, 1134.4 Å, and 1135.0 Å) and Ca II (1135.5 Å and 1135.6 Å) from the Galactic ISM is present in the FUSE spectrum (narrow lines in Figure 1), but there is no corresponding strong absorption in the NGC 1399 frame (1140 Å, with a width of 1.3 Å). The same can be said of C II λ1036 Å and O I λ1039 Å (only Galactic features are present). Thus, the N II and N III spectral indices have little, if any, contribution from an ISM in NGC 1399, and should track photospheric abundances only.

4.2. *Cooling Flow Emission*

NGC 1399 lies at the center of the Fornax cluster. The X-ray luminosity of the galaxy implies a large cooling flow, with a mass deposition of at least 2 $M_\odot$ yr^{-1} (Bertin & Toniazzo 1995; Rangarajan et al. 1995). Cooling flow models predict that this X-ray emission should be accompanied by O VI $\lambda\lambda$1031.9,1037.6 Å emission, radiated as the hot gas cools from $\sim 10^7$ K to $\sim 10^5$ K. Bregman, Miller, & Irwin (2001) did not find such emission in their FUSE observations of NGC 1404 (upper limit 0.3 $M_\odot$ yr^{-1}), an elliptical galaxy near the center of the Fornax cluster, but its X-ray luminosity suggests a smaller cooling flow deposition rate than that for NGC 1399 (Bertin & Toniazzo 1995). Thus, NGC 1399 offers a better opportunity for finding the warm gas from the Fornax cooling flow.

We see no O VI emission in our NGC 1399 spectrum (Figure 2); indeed, the observed flux at the location of the 1032 Å (rest frame) component is slightly lower than the expected flux from the stellar continuum. To set upper limits, we first fit an EHB model with the abundances determined above. The fit region was from 1035–1045 Å, and we included C II and O I absorption lines from our own Galactic ISM. Note that these strong Galactic features are not accompanied by equivalent features in the NGC 1399 frame, again implying a lack of a cold ISM. Once the best fit was achieved, these components were fixed, and then two components representing the O VI

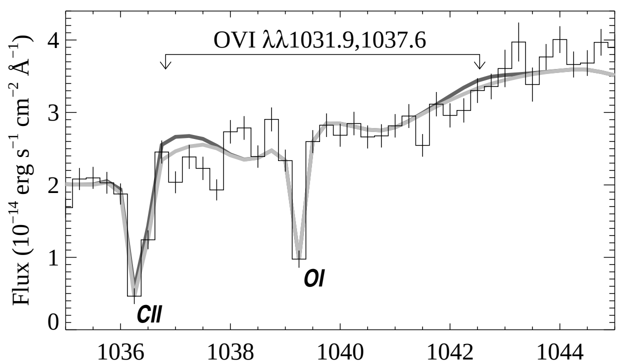

FIG. 2– The NGC 1399 spectrum at the expected location of O VI emission (histogram with error bars). The curves show the stellar model (light grey), including Galactic ISM absorption (italic labels), and the 3σ upper limit to the redshifted 0 VI emission (dark grey).

doublet were added. The wavelengths and widths were fixed at the NGC 1399 redshift and velocity dispersion, and the flux ratio was fixed at 2:1 for the 1032 and 1038 Å components. We find a 3σ upper limit of $f_{\lambda 1032} = 2.6 \times 10^{-15}$ erg s^{-1} cm^{-2} (and thus $f_{\lambda\lambda 1032,1038} = 3.9 \times 10^{-15}$ erg s^{-1} cm^{-2} for the total O VI emission). As in Bregman et al. (2001), we assume that $L_{\lambda 1032} = 0.9 \times 10^{39} \dot{M}$ erg s^{-1} (a compromise between the relations for isochoric and isobaric cooling). Thus, the 3σ upper limit to the mass deposition rate implied from the O VI emission is 0.14 $M_{\odot}$ yr^{-1}, for the 3×3 kpc region sampled by the FUSE aperture (assuming $m - M = 31.52$ mag; Ferrarese et al. 2000). The limit becomes twice as large if the fit is restricted to the cleaner region around 1038 Å. Models of the X-ray luminosity imply a larger rate of ≈ 0.4 $M_{\odot}$ yr^{-1} within the FUSE aperture (Rangarajan et al. 1985).

5. DISCUSSION

We have obtained the first clear detection of metallic absorption features in the UV upturn. The photospheric composition of the hot population in NGC 1399 appears to reflect that seen in the field sdB stars of the Milky Way. In the nearby Galactic field population, sdB and sdO stars often show moderate to severe depletions of the light elements, attributed to diffusion. Typically, N appears near solar abundance, while C and Si are depleted (Lamontagne et al. 1985; Lamontagne et al. 1987).

Several other processes could skew the photospheric abundances in EHB stars. Greggio & Renzini (1990) noted that hot HB stars of high metallicity would have very thin H envelopes; these could be wind-ejected at mass-loss rates of $\sim 10^{-10}$ $M_{\odot}$ yr^{-1}, resulting in surface compositions rich in He and N and poor in C and O. CN processing on the RGB is another possible effect (Sweigart & Mengel 1979). Assuming initial abundances at the solar C:N ratio and C+N nuclei conservation, the observed C and N abundances would imply primordial abundances of 0.12 solar, in the absence of diffusion.

Galactic field sdB stars tend to show depletion of the light elements from their original near-solar abundances, but little is known about the effects of diffusion on metal-poor EHB stars, because EHB stars in globular clusters are too distant to obtain spectroscopy easily. Diffusion is the largest uncertainty when associating the photospheric abundances of EHB stars with their primordial abundances. The photospheric abundance of a given element can be affected by both gravitational settling and radiative levitation, and thus the photospheric abundance can be either reduced or enhanced relative to the primordial abundances that drive the evolution of a star. Some calculations have shown that abundance enhancements via radiative levitation can be especially strong in the low-metallicity regime, because the absorption lines are not saturated (Michaud, Vauclair, & Vauclair 1983).

Taken at face value, our photospheric abundances do not resolve the metallicity debate for the origin of the UV upturn; they are neither extremely metal-poor nor extremely metal-rich. Tying these photospheric abundances to formation abundances will require further theoretical and observational work. In particular, UV observations of sdB stars in globular clusters are needed to demonstrate how the light elements are affected by diffusion processes in the metal-poor regime, showing whether gravitational settling or radiative levitation dominates. However, given the tendency for light element abundances to be diminished by diffusion, it seems unlikely that the UV emission in NGC 1399 comes from EHB stars with extremely low formation abundances (e.g., at $-2.4 < [\mathrm{Fe/H}] < -1.0$, as suggested by Park & Lee 1997); it seems more plausible that these stars started with high abundances that were then depleted, but at this point such conclusions are very speculative.

NGC 1399 is thought to be the center of a cooling flow in Fornax. Our upper limit to the O VI emission in the FUSE aperture is lower than expected from simple cooling flow models of the X-ray emission. Bregman et al. (2001) suggested that the lack of O VI emission in NGC 1404 could be due to an additional source of heating, but noted that NGC 1404 has no detected central radio source. NGC 1399 hosts a two-lobed radio source (Sadler, Jenkins, & Kotanyi 1989), which may help explain the lack of O VI emission.

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