The Hot Stellar Component in Elliptical Galaxies and Spiral Bulges

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Abstract. Suggestions for the source of the ultraviolet flux in elliptical galaxies and spiral bulges include young stars, post-asymptotic-giant-branch (PAGB) stars, hot-horizontal-branch stars, and accreting white dwarfs. Each candidate has different implications for the spectral evolution of galaxies. We review current understanding of the origin of the far-UV flux, with emphasis on recent results from the Hopkins Ultraviolet Telescope (HUT), flown on the Astro-1 space-shuttle mission in December 1990.

The origin of the far-ultraviolet light in elliptical galaxies and spiral bulges poses one of the most serious challenges to our understanding of the evolution of the stellar populations in these systems. UV observations from the *OAO-2, IUE*, and *ANS* satellites have shown that these systems typically have an upturn in their spectra shortward of 2000 Å, with flux increasing to shorter wavelengths (see Burstein *et al.* 1988 and references therein). The galaxy surface-brightness profiles are similar, but not identical, in the optical and UV, but the strength of the upturn varies from galaxy to galaxy. Galaxies with similar optical colors can differ by up to 2.5 magnitudes at 1500 Å. Galaxies with high metallicities tend to have bluer 1550 Å$-V$ colors than those with low metallicities.

Possible contributors to the UV flux include 1) young hot stars, presumably forming as a minority population from the reprocessed gas shed from the old population; 2) post-asymptotic-giant-branch (PAGB) stars similar to the central stars of planetary nebulae; 3) hot horizontal branch (HB) stars, either from the metal-rich population that dominates the optical light, or from a minority metal-poor population or 4) accreting white dwarfs. These possibilities and variations upon them have recently been reviewed in great detail by Greggio and 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. HUT produces one-dimensional spectra from the galactic Lyman-limit to 1860 Å with a resolution of ~ 3 Å. During the Astro-1 space shuttle mission in December 1990, we used HUT to obtain long exposures of NGC 1399 and the bulge of M31, and shorter exposures of several other galaxies and globular clusters. Most of the galaxies were observed through a $9'' \times 116''$ aperture centered on the nucleus. First results for NGC 1399 are described by Ferguson *et al.* (1991) . Here we summarize these results, and present a comparison of the NGC 1399 spectrum to other spectra obtained.

NGC 1399 has the strongest UV upturn of the "quiescent" ellipticals analyzed by Burstein *et al.* (1988). The HUT spectrum of NGC 1399, binned over 10 Å, is shown in Fig. 1. To set limits on the amount of present-day star formation, we have constructed synthetic spectra using an "isochrone synthesis" technique similar to

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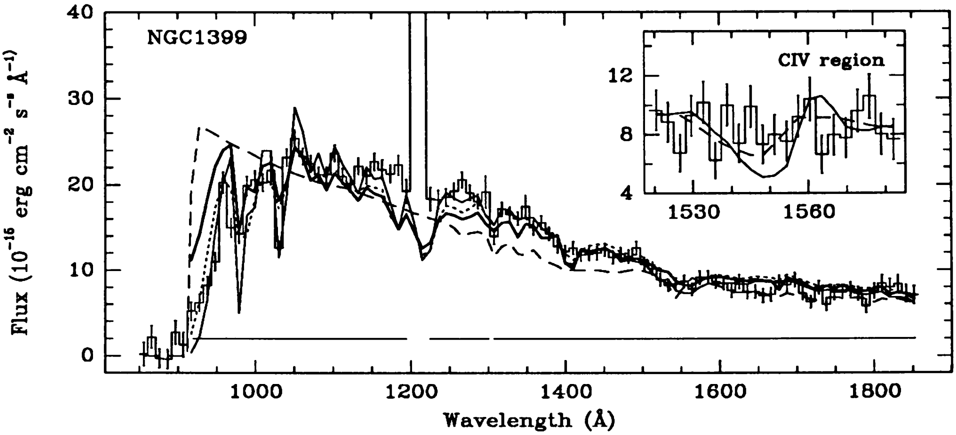

Fig. 1. HUT spectrum of NGC 1399. The histogram in the main figure is the flux-calibrated HUT spectrum, binned at 10 Å intervals. The solid line shows the best-fitting solar-metallicity Kurucz (1991) model atmosphere. The model parameters are $T_{\text{eff}} = 24000$ K, and $log(g) = 4.0$. Regions used in the fit are indicated by the horizontal line at the bottom of the plot; regions contaminated by strong airglow lines were excluded. The dashed line shows the RG hot-E model at an age of 13 Gyr. 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 $M_{upper} = 20 M_\odot$. Finally, the thick solid line shows a synthetic spectrum of a population of $0.546 M_\odot$ PAGB stars. 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 timescale $\tau = 2.7$ Gyr).

that of Charlot and Bruzual (1990). Evolutionary tracks for high-mass stars from Maeder and Meynet (1988) (hereafter MM) were used, with bolometric corrections taken from Humphreys and McElroy (1984) and Flower (1977). Constraints on the young star population can be set by considering the entire spectral-energy distribution (SED), or just the region near C IV $\lambda 1550$, the strongest absorption line in the hot stars that should be contributing. Comparison with the SED has the danger that it must rely on stellar atmosphere models (Kurucz 1991) that may not match the metallicity of the population, and that are in any case poorly tested below Lyα. Furthermore, the uncertainties in extinction and the absolute HUT calibration are greater shortward of the IUE spectral range. On the other hand, the comparison near C IV, while mostly free from uncertainties in extinction and calibration, is hampered by low signal-to-noise and the possibility that the IUE spectral library (Heck *et al.* 1984) used to construct the synthetic spectrum does not match the metallicity of the stellar population.

Figure 1 (inset) shows the region around C IV 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 2σ upper limit is that stars from this model can be responsible for no more than 50% of the 1550 Å flux (less if

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the component producing the rest of the light also has intrinsic C IV absorption). The dashed line shows the RG hot-E model, which is excluded at the 95% confidence level.

Comparison of the NGC 1399 SED to individual Kurucz (1991) solar-metallicity models suggests that stars cooler than $\sim$ 25000 K are the dominant contributors to the UV upturn. The best-fit model is shown as a solid line in Fig. 1. This temperature limit, set mostly by the turnover below 1000 Å, is consistent with the absence of C IV absorption. Stars hotter than $\sim$ 28000 K would probably have detectable C IV, especially if they are metal rich. The shape of the SED limits the number of massive stars that can be evolving at present along the main sequence in NGC 1399. The dashed line in Fig. 1 shows that the RG hot-E model far overshoots the continuum below 1000 Å. 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 1) has $M_{upper} = 20 M_{\odot}$ and an IMF slope $x = -0.1$; however, such a sharp upper-mass cutoff on an IMF that is weighted toward massive stars seems implausible.

The turnover near the Lyman limit also imposes a serious constraint on PAGB models, since these stars are typically much hotter then 25000 K. 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) model for 0.546 $M_{\odot}$ stars is shown as a heavy line in Fig. 1. The match to the data becomes progressively worse for higher mass PAGB stars. 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 the SED; high-temperature metal-rich PAGB stars with enough of an envelope left to produce the Lyman lines and C III λ1175 (easily seen in the raw data) 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.

Further constraints on the UV stellar population may come from comparing the SED's of different galaxies. We have made a first cut at this for the low S/N spectra obtained of the centers of NGC 1316, and M 81, and the high-quality spectrum of M 31. In M 81, the continuum flux drops gradually from 1200 Å to the Lyman limit, probably due to internal extinction. The NGC 1316 SED is quite similar to NGC 1399's, but a quantitative comparison will require careful modelling of the contribution from scattered geocoronal Lyα. Figure 2 shows the ratio of the M 31 flux to the NGC 1399 flux as a function of wavelength. M 31 has significantly more flux than NGC 1399 near the Lyman limit. It is unlikely that errors in extinction can explain this difference, unless the extinction curve is radically different from that measured in our own galaxy. We conclude that the stars producing the strong UV upturn in NGC 1399 are not just "more of the same" type of stars that produce the upturn in M 31. Hotter stars are allowed in M 31, and, while we have not yet fit models in detail, it is possible that low-mass PAGB stars could contribute significantly. The population producing the *excess* flux in NGC 1399 must be significantly

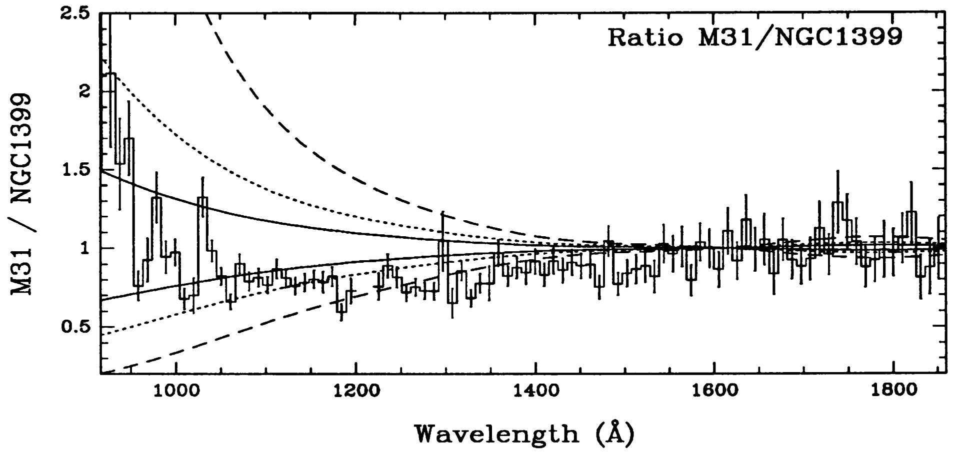

Fig. 2. The ratio of the M 31 spectrum to NGC 1399, normalized such that the mean is 1.0 between 1500 and 1700 Å. The M 31 spectrum has been corrected for galactic extinction, but not for internal extinction or contamination by disk light (both of which are probably small effects). The curves that bend upwards at short wavelengths show the deviation expected from a constant value of 1.0 if NGC 1399 were subject to extinction following the galactic curve of Longo *et al.* (1989). The solid, dotted, and dashed lines correspond to reddenings of $E(B-V) = 0.05, 0.1$, and 0.2 mag, respectively. The curves that bend downwards show the ratio expected if M 31 were subject to additional extinction. The fact that none of the extinction curves match the shape of the M 31/NGC 1399 ratio suggests the excess flux near the Lyman limit in M31 is due to hotter stars, rather than errors in the extinction correction.

cooler, and is unlikely to be PAGB stars or young stars, for the reasons discussed above.

Acknowledgements

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Discussion

Gregg: NGC 1316 is known to have a lot of dust, so how do you explain the similarity of its UV spectrum and that of NGC 1399?
Ferguson: NGC 1399 is a magnitude fainter in B than NGC 1316, but its 1400 Å flux is about factor of 4.5 brighter, so I think NGC 1316 probably is affected by extinction. The fact that the UV spectral energy distributions are similar suggests that the intrinsic slope of the upturn may be steeper in NGC 1316, but I should caution that the spectral-energy-distribution I showed was based on a very low S/N spectrum and the airglow contribution has not yet been carefully modeled.
Whitelock: I don't think you should reject the accreting WD hypothesis on the basis of supernova rates. Accreting symbiotic WD's within the galaxy undergo periodic shell flashes and eject much of the material they have accreted. They may therefore not be SN progenitors.
Pinsonnealt: We have computed evolutionary models of metal-rich HB stars. Their high metallicity and helium accelerates H-burning, causing them to skip the AGB phase and become hot stars on the He-burning main sequence. Because these stars are both fainter ($\sim 100 L_{\odot}$) and long lived ($\sim 10^7$ years) their properties differ from the post-AGB models you have discussed. These results depend on age, metallicity and $\Delta Y/\Delta Z$, and will also affect the integrated colors by removing the AGB light.