UV Spectral Dating of Stars and Galaxies†

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ABSTRACT

An echelle spectrogram (R = 30,000) of the 2300–3100 Å region in the ultraviolet spectrum of the F8V star 9 Comae is presented. The observation is used to calibrate features in the mid-ultraviolet spectra of similar stars according to age and metal content. In particular, the spectral break at 2640 Å is interpreted using the spectral synthesis code synspec. We use this feature to estimate the time since the last major star formation episode in the z = 1.55 early-type galaxy LBDS 53W091, whose rest frame mid-ultraviolet spectrum, observed with the Keck Telescope, is dominated by the flux from similar stars that are at or near the main-sequence turnoff in that system (Spinrad et al. 1997). Our result, 1 Gyr if the flux-dominating stellar population has a metallicity twice solar, or 2 Gyr for a more plausible solar metallicity, is significantly lower than the previous estimate and thereby relaxes constraints on cosmological parameters that were implied by the earlier work.

Subject headings: galaxies: evolution — galaxies: stellar content — ultraviolet: galaxies — ultraviolet: stars — stars: atmospheres
1. Introduction

Elucidating the formation and evolution of galaxies is a prime goal of the Hubble Space Telescope and other major telescopic facilities. To accomplish this, it is important to obtain and interpret spectral information on distant galaxies that may be in early phases of evolution. The very red radio galaxy, LBDS 53W091 at redshift \( z = 1.552 \), recently examined spectroscopically in the rest frame ultraviolet with the Keck Telescope (Dunlop et al. 1996; Spinrad et al. 1997), is a potential milestone in this work. These observations may constrain the earliest epoch of star formation, and thereby, perhaps, cosmological parameters. To interpret such spectra, it is necessary to understand what stellar population(s) contribute to them. This can be approached by obtaining ultraviolet spectra of suitable quality of nearby stars whose nature is well understood.

The Keck spectrum of galaxy 53W091 is remarkably similar to the rest frame ultraviolet spectrum of a mid-to-late F star. The similarity is quite strong near 2600 Å, although the spectrum becomes a composite of later types (late F to early G) near 2900 Å. It clearly shows the principal absorption features of Mg I and Mg II, and the two well-known spectral breaks at \( \lambda_{\text{rest}} = 2640 \) and 2900 Å. This marked resemblance of a galaxy spectrum to that of stars from a small range in stellar types is due to the overwhelming contributions in the mid-ultraviolet spectrum of intermediate-age stars near the main sequence turnoff. Since the temperature or spectral type at the turnoff is a prime age indicator for a coeval population, the dominating fluxes of such stars in the mid-ultraviolet have obvious application to dating unresolved stellar systems.

The Keck observers of 53W091 derived an age of at least 3.5 Gyr since the last epoch of major star formation in that system. An age that great would rule out cosmologies with deceleration parameter \( \Omega = 1 \) and Hubble constant \( H_0 \geq 50 \) km \( \text{s}^{-1} \text{Mpc}^{-1} \). Such a strong conclusion deserves further test. In particular, it is desirable to make an improved calibration of the mid-ultraviolet spectra of F-type stars, to support the application of this dating method to this and other distant galaxies. Fanelli et al. (1992) used low-resolution IUE spectra to show that the spectral breaks at 2640 and 2900 Å correlate with spectral type (temperature) but are only mildly sensitive to metallicity. To refine and extend this calibration with the first-generation spectrographs on the Hubble Space Telescope appeared impractical. However, thanks to the multiplex advantages of an imaging spectrograph, we have initiated a program to this end with the Space Telescope Imaging Spectrograph (STIS).

Our STIS General Observer program \#7433 will obtain mid-ultraviolet spectra of twelve F-type stars of known atmospheric properties at a resolution \( \lambda/\Delta \lambda = 30,000 \). Here we report representative observations of one such star, 9 Comae (metal rich, F8V). With these results, we improve the mid-ultraviolet calibration of this and related stars and thereby conclude that the corresponding rest frame spectrum of 53W091 is compatible with a much younger age \(( \lesssim 2 \) Gyr) than reported by Dunlop et al. (1996) or Spinrad et al. (1997). This relaxes the strong constraints on cosmology that were implied by the earlier work.

2. Observations & Reduction

The F8V star 9 Comae (HR 4688, HD 107213) is expected to resemble the stars responsible for the rest frame mid-ultraviolet spectrum of 53W091. Its atmospheric properties (Edvardsson et al. 1993) are well known: \( T_{\text{eff}} = 6343 \) K, \( \log g = 4.05 \), \( [\text{M/H}] = +0.28 \) and \( [\text{Fe/H}] = +0.21 \). The star lies at a Hipparcos distance of 49.7 pc, well in front of the open cluster Mel 111. The age of 9 Comae is estimated at 1.6–2.4 Gyr depending on whether it is on the “blue hook” in the HR diagram or still on the main sequence (c.f. Figure 1). Because this star is metal-rich, its STIS spectrum provides a stringent test of the completeness of the atomic and molecular
line list used in its interpretation. However, we note that the star is somewhat more metal-rich than the abundances expected in the integrated spectrum of 53W091. Many studies (González & Gorgas 1995 and references therein) suggest that there is a radial metallicity gradient in elliptical galaxies. Since the Keck spectrum was observed through an aperture that integrated out to the effective radius, the “average” metallicity in the Keck spectrum is probably close to solar.

Fig. 1.— 9 Comae (star symbol) on the HR diagram, plotted in the traditional way (left) and in the $T_{\text{eff}}$-$\log g$ plane (right). The four isochrones (Yi & Demarque 1997) are for [M/H] = +0.3 and ages of 1, 2, 4, and 8 Gyr (top to bottom).

The STIS ERO observing program #7139 on 9 Comae was accomplished within a single 96-minute orbit of the HST. During this period, the star was located with the STIS CCD detector, the pointing of the Telescope was adjusted to place the stellar image in the $0^\prime.2 \times 0^\prime.063$ entrance slit, and the spectrum was recorded by the near-ultraviolet MAMA detector. The total integration was 20 minutes, divided into two sub-exposures of ten minutes each. The resulting echellogram covering the spectral region 2280–3110 Å is shown in Figure 2 (Plate XX).

At the time of observation, 1997 May 31, the operating procedures to “peak-up” a target in a STIS entrance aperture were not yet optimized. Accordingly, the fraction of the light in the stellar image that was transmitted through the aperture was less than the nominal value applicable when STIS is fully commissioned. Nevertheless, the signal-to-noise ratio in the continuum is 40 per pixel above 2800 Å, and 15 shortward of 2600 Å. Again, because STIS was not fully operational at the time of observation, the doppler compensation program that adjusts for the changing velocity vector of the spacecraft during the observation was not active. However, any smearing due to spacecraft motion in this spectrum is less than the rotational velocity of 9 Comae or the nominal 2-pixel resolution (10 km s$^{-1}$) of the spectrograph in this mode.

The STIS Investigation Definition Team version of the CALSTIS program was used to reduce the spectrum through the stage of extracting the spectra from the various grating orders and subtracting the inter-order spectral background. Next, we corrected for the echelle blaze function by Barker’s (1984) method and merged the data from the various orders into a single spectrum comprising almost 20,000 data elements. In this spectrum, saturated absorption lines reach only to a residual intensity $I = 0.03$ rather than to zero. This may be due to instrumental scattered light associated with the echelle grating. Alternatively, it may result from chromospheric emission in the cores of the strong lines (chromospheric emission is quite obvious in the cores of the Mg II $\lambda\lambda$2795,2803 doublet).

As an in-orbit radiometric calibration is not yet available for STIS mode E230M spectra, we calibrated the observation using component sensitivities measured before launch by the STIS team. Figure 3 shows the derived relative flux distribution of 9 Comae, binned to 1 Å resolution. Due to the uncertainty in calibration, we concentrate our analysis on the two spectral breaks B(\lambdastar2640) and B(\lambdastar2900) that were used to date the time since the last major star-forming event in 53W091 (Spinrad et al. 1997). These two features, also shown in Figure 3, are insensitive to errors in flux calibration and interstellar reddening.
Fig. 2.— STIS echellogram of 9 Comae. The gray-scale is reversed so that the brightest regions are black. Wavelength increases to the right (within an order) and down (from order to order).
Fig. 3.— STIS E230M spectrum of 9 Comae, binned to 1 Å. The 2640 and 2900 Å breaks of Spinrad et al. (1997) are illustrated by the shaded panels (ratio of the integrated flux longward of the break to the flux shortward of the break).

3. Analysis

What are the constituent absorbers in the spectral breaks? Why do they show the observed trends with spectral type? Can the observed spectral breaks be reproduced by model spectra at the correct temperature, gravity, and metallicity? Are the spectral breaks reliable indicators of age? To help answer these questions, we computed the high-resolution spectra for comparison to STIS observations. To generate the synthetic spectra, we applied our spectral synthesis program, synspec (Hubeny 1988; Hubeny, Lanz & Jeffery 1994) to fully line-blanketed model atmospheres provided by Kurucz (1993).

For this application, we assumed LTE for all ions, and we used line opacities as derived from the Kurucz (1993) line list. We used all lines (those originating between predicted as well as measured levels) for Fe I, Fe II, and Ni II, but only lines originating between measured levels for other metals. We made extensive tests to verify that this simplification does not lead to any appreciable errors. We included all relevant molecular lines from Kurucz’ (1993) data set. We calculated continuum opacities using energy levels and cross-sections from the TOPbase inter-

face (Cunto et al. 1993) to the Opacity Project database. To ensure that continuum edges were properly placed, we shifted the theoretical energy levels in TOPbase to match the laboratory measurements of Martin et al. (1995).

Figure 4 compares the model spectrum of 9 Comae to a sample segment (2870–2880 Å) of the STIS spectrum, shown at full resolution. While most features are readily identified, often there is an observed spectral feature that is not reproduced by the model, and vice versa. We attribute this lack of correspondence to wavelength errors in the line list, since it appears to occur randomly and in both directions. In general, though, the match of model to observations is good enough that we can have confidence in the line identifications.

What causes the spectral breaks? Morton et al. (1977) identified the principal contributors to the features in this region, using Copernicus data. Our own models show that the spectral interval incorporated in the 2640 Å break has only one weak Fe I absorption edge, while the 2900 Å break contains only minor Mg I photoionization resonance features. Thus, the breaks are not a measure of the strength of continuum edges. Rather, they measure the chance agglomerations of lines. In the case of the 2640 Å break, the absorption trough is dominated by lines belonging to the UV1 resonance multiplet of Fe II, while longward of the break, the absorption is produced by subordinate Fe II lines and lines from other elements. The sensitivity of B(λ2640) to temperature is an excitation effect in Fe II, the dominant ion of Fe. At increasing temperatures, the excited states of Fe II become populated at the expense of the ground-state population.

Figure 5 compares our synspec results (assuming the abundances of Edvardsson et al. 1993) to the observed UV breaks in the spectrum of 9 Comae. The model reproduces the two spectral breaks for the temperature, gravity, and elemental abundances of 9 Comae, implying that the model is essentially correct. Furthermore, it
faithfully follows the observed trends of $B(\lambda 2640)$ with temperature (Fanelli et al. 1992; Spinrad et al. 1997). The SYNSPEC models also reveal a significant sensitivity to gravity, which might explain the dispersion in the observed measurements of $B(\lambda 2640)$ in luminosity-class V and IV stars. In contrast to the general agreement between the SYNSPEC models and STIS observation, Kurucz’ (1993) spectral energy distributions (SEDs) systematically overestimate the 2640 Å break and therefore should not be used to infer age from this diagnostic. Both the SYNSPEC models and Kurucz SEDs match the 2900 Å break in the spectrum of 9 Comae as shown. However, compared to observations presented by Fanelli et al. (1992) and Spinrad et al. (1997) both fail at temperatures below about 6000 K.

We calculated the UV spectra of stellar systems described by Yi & Demarque’s (1997) isochrones for metallicities of one and two times solar. These isochrones are similar to the Yale (Green, Demarque, & King 1987) isochrones, but with improved opacities. Figure 6 compares the resulting computed UV spectral breaks to the observed ones in the spectrum of 53W091. $B(\lambda 2640)$ yields an age of 1 to 2 Gyr depending on the assumed metallicity. $B(\lambda 2900)$ yields a much older age ($\geq 5$ Gyr) for 53W091, but this diagnostic, while useful in empirical studies, is not to be trusted here, since our SYNSPEC models (and Kurucz’ SEDs) do not match the observed values at temperatures lower than 6000 K. We will investigate this discrepancy once we obtain STIS UV spectra of cooler stars.
4. Conclusions and Future Work

In summary, the STIS spectrum of 9 Comae has verified our spectral model of a late F-type star near the main sequence turnoff; the 2640 Å break yields the same temperature and age as its location on the HR diagram. With this observational validation, we have computed the age-sensitive 2640 Å spectral break for stellar systems of various ages. Our derived age (≤ 2 Gyr) for the youngest stars in the early-type galaxy, 53W091, is considerably lower than estimated by Spinrad et al. (1997); consequently, it relaxes the constraints of cosmological parameters that were implied in that work.

This Early Release Observation suggests that future STIS observations will help to fine-tune stellar atmospheric models; this in turn will provide a direct conversion from UV spectral characteristics to the fundamental parameters of a star or stellar system. However, it also identifies important spectral modelling issues (e.g., the importance of chromospheric emission to age-sensitive features; the validity of assuming LTE; and most importantly, the adequacy of the atomic and molecular data) as well evolutionary modelling issues (e.g., the importance of convective overshooting). These issues can also best be addressed through future STIS observations.

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