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From Hubble's Next Generation Spectral Library (NGSL) to Absolute Fluxes

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Abstract. Hubble's Next Generation Spectral Library (NGSL) consists of $R \sim 1000$ spectra of 374 stars of assorted temperature, gravity, and metallicity. Each spectrum covers the wavelength range, $0.18 - 1.03\,\mu$. The library can be viewed and/or downloaded from the website, http://archive.stsci.edu/prepds/stisngsl/. Stars in the NGSL are now being used as absolute flux standards at ground-based observatories. However, the uncertainty in the absolute flux is about 2%, which does not meet the requirements of dark-energy surveys. We have therefore developed an observing procedure, data-reduction procedure, and correction algorithms that should yield fluxes with uncertainties less than 1%.

1. Introduction

The Next Generation Spectral Library (NGSL) is a collection of flux-calibrated stellar spectra based on observations made by Hubble's Space Telescope Imaging Spectrograph (STIS). The observations were obtained to provide an empirical basis for interpreting the integrated light of galaxies and star clusters. The observing program spanned three years, with Michael Gregg as the principal investigator for the first two years (GO 9088, 9786), and Dave Silva, the PI for the third year (GO 10222), which was cut short because of instrumental problems. Even so, the NGSL contains spectra of 374 stars, all observed in the same way, and all spectra covering the spectral range, $\sim 0.2 - 1.0\,\mu$, at a spectral resolving power, $R \sim 1000$. Section 2 describes NGSL observations in more detail, while Section 3 describes our construction of the spectral library.

Besides its obvious usefulness for stellar and galaxy studies (e.g. Koleva & Vazdekis 2012), NGSL spectra are starting to be used for spectrophotometric calibration at ground-based observatories (Bessell 2012; Bessell & Murphy 2012). The latter studies have stimulated discussions concerning absolute flux calibration of astronomical sources. This paper attempts to answer the questions: how good are the absolute fluxes of stars in the NGSL, and how might they be improved? And Section 4 summarizes the "lessons learned" from the NGSL for obtaining precise absolute flux standards.

2. NGSL Observations

STIS has many modes of operation such as long-slit, first-order spectroscopy; echelle spectroscopy in the UV; normal filter imagery and coronagraphic imagery. NGSL spectra were obtained in the long-slit, first-order mode. Three gratings (G230LB, G430L, G750L) are sufficient to cover the full spectral range of the CCD ($0.18 - 1.06\,\mu$) with modest overlap. At low resolution ($R \sim 1000$), the whole spectral range of a grating can be covered in one exposure. Table 1 gives a summary description of the three spectral segments, which we later merged into a single spectrum (§3).

Table 1. NGSL Observations

	G230LB	G430L	G750L
Detector	STIS CCD	STIS CCD	STIS CCD
Spectral Range (μ)	0.16-0.32	0.29-0.57	0.52-1.10
Spectral Dispersion (Å/pix)	1.35	2.73	4.92
$R = \lambda/\Delta\lambda$	500-1000	530-1040	535-1170
Aperture	52x0.2E1	52x0.2E1	52x0.2E1
Slit Width (arcsec)	0.20	0.20	0.20
Pixel size (arcsec)	0.05	0.05	0.05

NGSL observations were obtained as Hubble "Snapshots". The Hubble Snapshot Program was designed by John Bahcall and Rodger Doxsey as a means of increasing observing efficiency. The idea was to insert short observations, or "snapshots", into holes in the observing schedule that could not be filled by regular observing programs. The duration of a snapshot observation, including overheads, is less than 40 minutes, i.e. well less than an orbit (94 min). A snapshot proposer therefore lists numerous targets distributed over the sky, on the understanding that there is no guarantee that any particular target will be observed.

The NGSL snapshot program observed 378 targets (only 4 observations were unusable), but the normal observing sequence had to be shortened to fit into the observing schedule. Thus, there was no time to take wavelength-calibration exposures. Also, there was no time to "peak-up" the star in the slit. Hubble was simply commanded to slew the target coordinates given by the proposer. Unfortunately, the exact position of the E1 aperture was not measured until after the first year of observation, and the measurements indicated that the actual position of the slit was 0.03" away from the predicted position, so most target stars were not well centered in the 52X0.2E1 entrance slit. Finally, there was no time to read out the full CCD frame, so only the top 64 lines (in GO 9088) lines or 128 lines (in GO 9786, GO 10222) were read out, which meant that the background had to be sampled in a different location.

By the time that NGSL observations were obtained, STIS was already 5 years old, and damage to the CCD detector due to particle radiation was already evident. One form of damage is increased dark current. This was not a serious problem, since the NGSL targets are relatively bright stars needing only short exposures to obtain spectra having a $S/N > 100$. However, increased charge transfer inefficiency (CTI) posed a more serious problem. To reduce the number of charge transfers and thus, the CTI, scientists at the STScI defined a new position along the long slit that is close to the CCD readout registers. This new position is called "E1". NGSL observations of target stars were always taken with the target star at the E1 position of the 52x0.2 slit, which is 52” long and 0.2” or 4 CCD pixels wide. Even with HST’s fine spatial resolution, a 0.2-wide arcsec slit is not quite wide enough to transmit all the flux of a star even if it is perfectly centered in the slit, so absolute spectrophotometry is marginal at best. We estimate that systematic flux errors can reach 10-15%, but that these errors can be reduced to 2-3% with the aperture-correction procedures described in §3.2.

3. Construction of the Next Generation Spectral Library

3.1. Data Processing

Because of the non-standard observing procedure, NGSL observations required customized data-reduction procedures. In archival research programs, AR 10659 and 11755, we developed and applied the following improvements to the standard STIS pipeline processing to process individual NGSL observations:

- New spectral trace files were produced and used. These were constructed from the average spectral y-position versus x-position for the 52X0.2E1 aperture for all of the NGSL stars.
- Custom fringe flats were constructed for each of the G750L observations using the tungsten lamp observation associated with the visit.
- A more appropriate background subtraction was used. The standard pipeline uses only a lower background taken 300 pixels below the spectrum for the E1 aperture position. We used both an upper and lower background taken much closer to the spectrum (30 pixels).
- A larger extraction slit height (11 instead of 7) was used to improve overall photometric precision at the cost of some loss in S/N.
- Custom wavelength dispersion coefficients were created for the E1 aperture position.
- Since wavecals were not taken with the stellar observations, zero-point offsets were computed for each spectrum from the positions and wavelengths of strong stellar features.
- Custom sensitivity curves applicable to our background subtraction method were created for the 52X0.2E1 aperture using observations of BD+75D325 centered in the aperture.

After routine pipeline processing, we constructed the final, composite spectrum, taking the following steps:

- The observations for each grating were obtained at two slightly different y-positions along the slit. These were co-added after rejection of cosmic rays and hot pixels.
- The observations of the three gratings were merged with an average taken in the overlap region (2990- 3060 Å for G230LB and G430L, 5500-5650 Å for G430L and G750L).

- A correction was performed for the slit throughput for targets not centered in the slit (§3.2)

- In-order grating scatter was subtracted for G230LB (§3.3).

3.2. Aperture Offset Correction

3.2.1. Version 1

In the middle of our first archival program (AR 10659), we discovered that the relative flux distributions did not always match model flux distributions. What was particularly noticeable was a "red wave", where the observed flux distribution was higher than the model, with the peak difference up to 10-15% occurring at about 8,000 Å. By the time this anomaly was discovered, STIS was not operational, so there was no chance to make new observations to diagnose the problem. We could only use the data in hand. But it turned out that the NGSL data sufficed, as it showed the wavelength-dependent flux error (observed - model) was correlated with position of the target star in the slit.

Fortunately, we could measure the offset of the targets from the center of the slit using the G750L fringe-flats taken with the observation. If a target is centered in the slit, the fringes in the flat-field observation are aligned with the fringes in the stellar observation. If the target is off center, the offset between the fringes in the flat and in the stellar spectra gives the offset within the slit. We found that in the first year of NGSL observations, the typical offset of a star from slit center was 0.6 CCD pixels. For comparision, the slit is only ±2 pixels wide.

In AR 10659, we worked to derive a wavelength-dependent correction to the slit throughput as a function of offset from the slit center. To correct the flux at wavelengths above 5700 Å, we used best-fit stellar models (using only the data below 5700 Å to determine the model parameters). We compared the ratio of the calibrated NGSL spectra to the model for wavelengths above 5700 Å. We fit a smooth spline curve versus slit offset to determine a correction for each wavelength bin. These corrections were then applied to the calibrated spectrum.

In February 2008, we delivered Version 1 of the NGSL to MAST. The Version 1 library contains the spectra of 374 stars produced by custom pipeline processing and post-pipeline processing including the predicted correction for the slit throughput as well as correction for grating scatter.

3.2.2. Version 2

With the repair of STIS in the last Hubble Servicing Mission (SM4) in 2009, we were able to obtain calibration data (GO/CAL 11652) to characterize the wavelength-dependent throughput of the 0.2"-wide slit versus the position of the target within the slit. We obtained this information from observations of a standard star, BD+75D325, which was stepped across the slit. In program AR 11755, we first determined the amount by which each NGSL star is off-center using the location of fringes in the long wavelength (G750L) spectra, made corrections for UV grating scatter (§3.3), made other improvements as described in §3.4, and derived the absolute flux distribution of each NGSL star. We delivered this new version of the NGSL to MAST in April 2010.

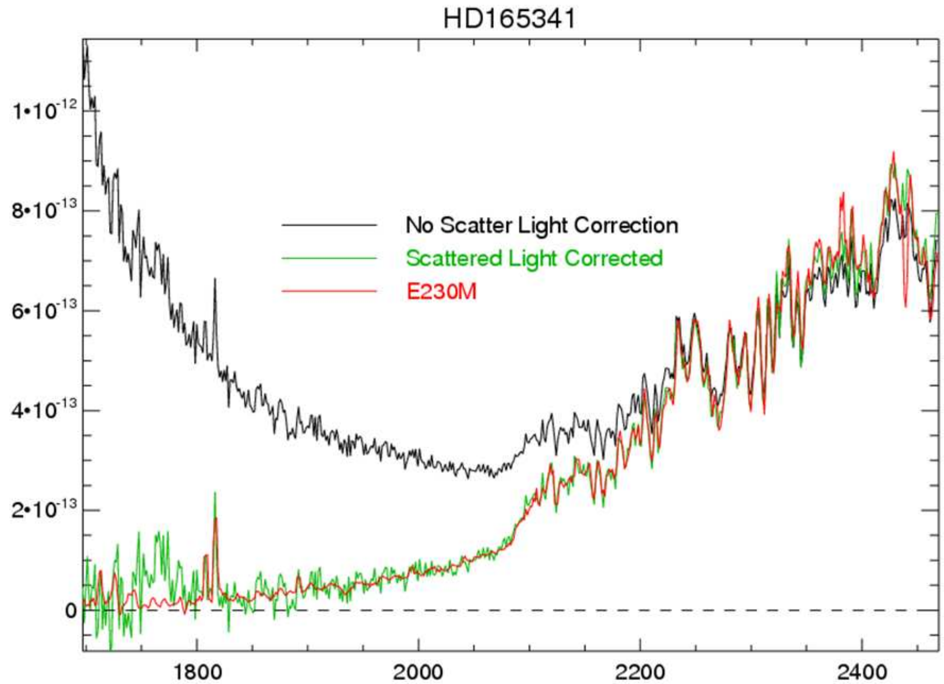

Figure 1. UV scattered light correction. The upper (black) curve shows the UV spectrum of HD 165341 before correction for grating scatter, while the lower (red) curve shows the STIS spectrum of the same star observed in the echelle E230M mode with the NUV solar-blind MAMA detector. The green curve shows the NGSL spectrum after correction for grating scatter.

3.3. Grating Scatter

The ultraviolet portion of a NGSL spectrum is useful not only for deriving the properties of the stars but also for getting a good handle on the dust extinction on the line of sight to the star. However, the UV spectral region (G230LB) is most vulnerable to in-order grating scatter. Scattered light is particularly evident in the UV spectra of very cool stars. We have modeled this scatter and applied it to observations of all the NGSL stars. Details are given at the NGSL website. Figure 1 compares the observed and corrected spectrum of a NGSL star that was also observed by STIS at higher resolution (E230M) and with the solar-blind MAMA detectors. It is clear that the correction is highly effective.

3.4. Other Improvements

Recently, Hipparcos data were re-reduced resulting in improved distances (van Leeuwen 2007). The new Hipparcos catalog is important to the NGSL, as nearly all NGSL stars have distances from Hipparcos, and distances are used to estimate the surface gravities of NGSL stars. We have derived the atmospheric parameters, T_{eff}, log g, and [Fe/H], and the color excess, E(B-V) of each NGSL star using the method of full-spectrum fitting, which works to fit the broad-band continuum as well as the line spectrum. This approach is appropriate for low-resolution spectra, but it places a special burden on the

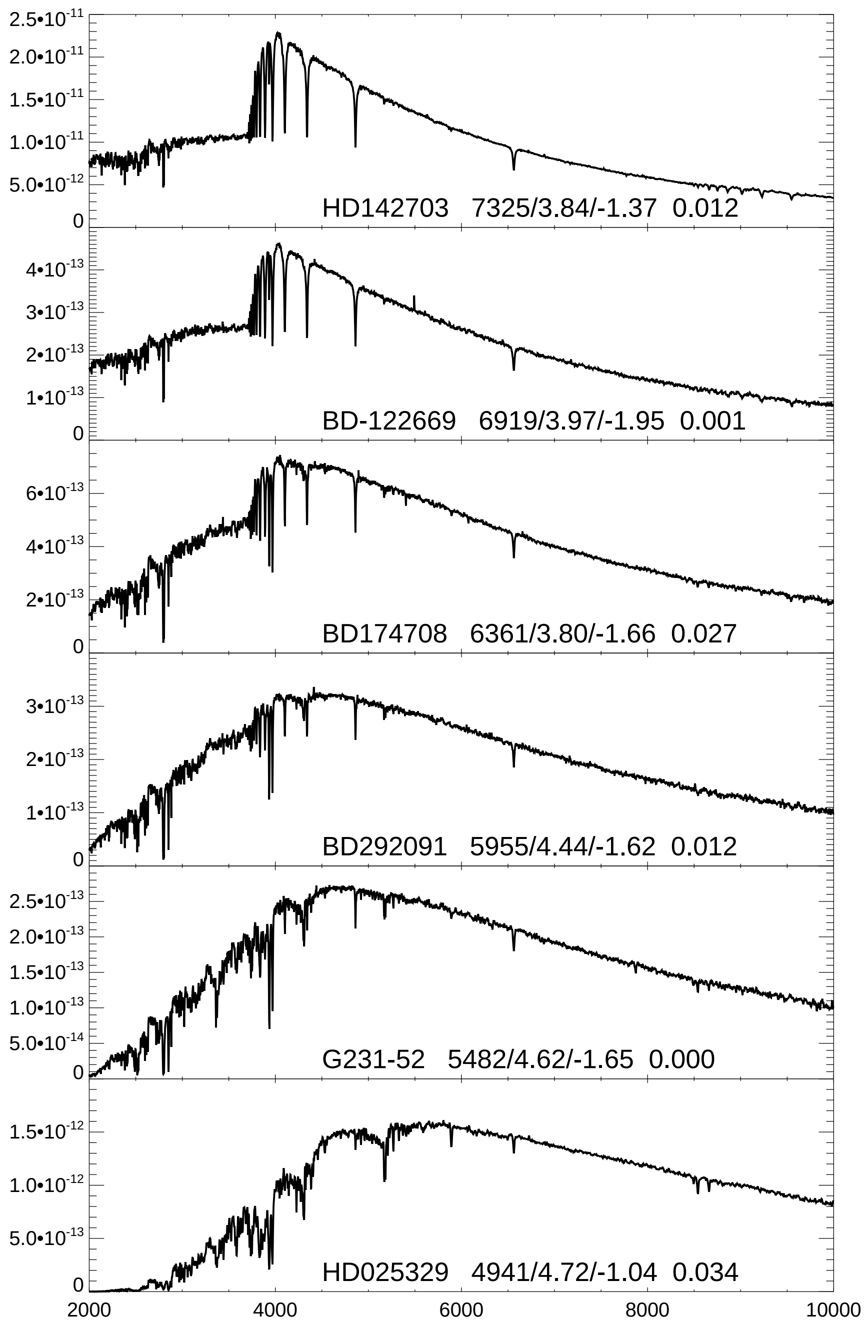

Figure 2. Version-2 NGSL spectra of main-sequence stars of low metallicity. The label in each panel gives the name of the target star, its atmospheric parameters, T_{eff}/ log *g*/ [Fe/H], and color excess, E(B-V). These parameters were derived from full-spectrum fitting with MARCS model spectra.

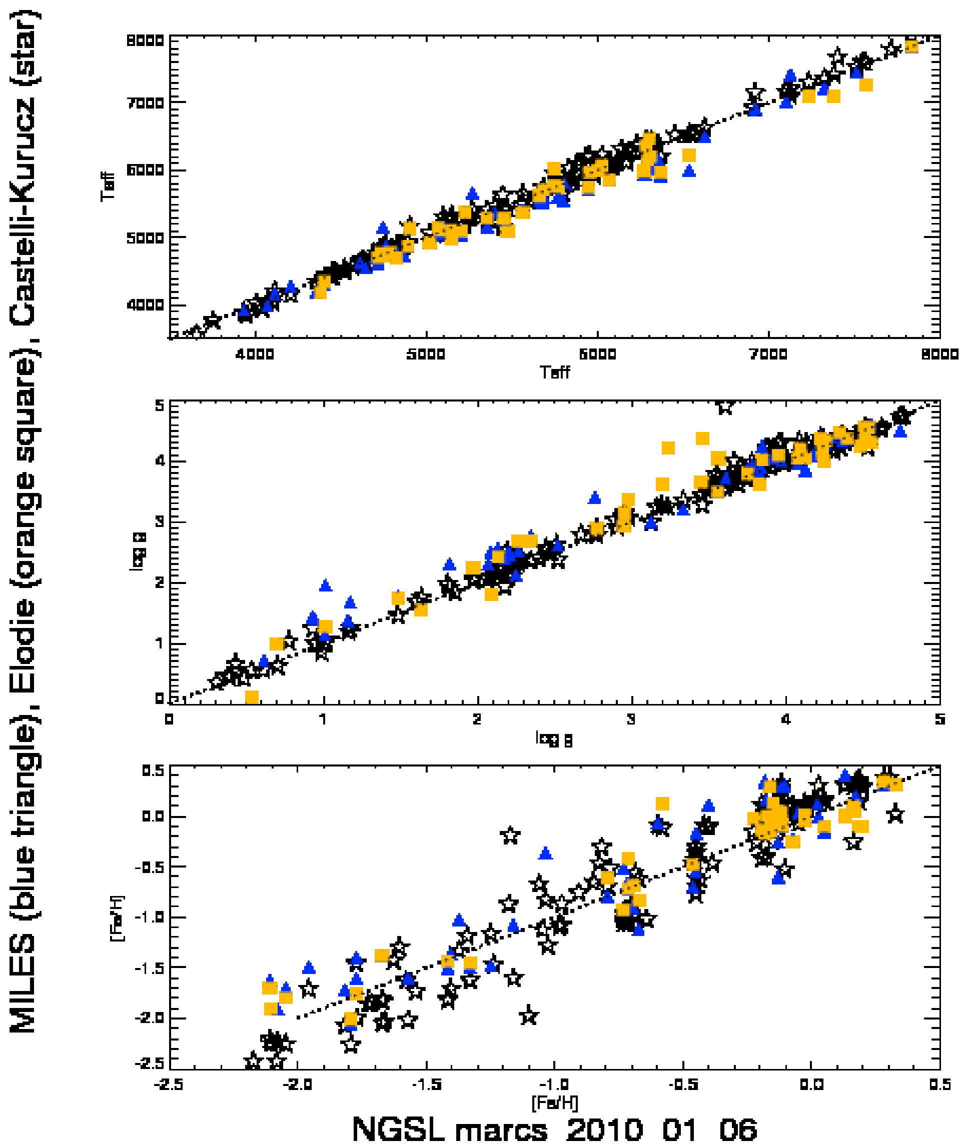

Figure 3. Comparison of stellar atmospheric parameters derived from NGSL spectra vs. other estimates.

quality aperture correction (§3.2), since the main effect of an offset of a star from the center of the slit is to alter the continuum flux distribution. We found, in fact, large differences between the stellar parameters derived Version 1 and Version 2 of the library.

In full-spectrum fitting, a least-squares fit attempts to minimize the RMS difference between a model spectrum and the observed spectrum (both normalized to an average of 1.0 in the range of 4500 to 7000 Angstroms). We restricted candidate models to those falling on a BASTI isochrone, and we derived the isochrone surface gravity on the assumption that the target distance is within a two-sigma error of the distance in the new Hipparcos catalog. For the model spectra, we first used the Castelli-Kurucz (2004) grid of low-resolution model spectra, which cover the temperature range, $T_{eff} = 3,500 - 50,000$ K. For stars cooler than 8,000 K, we also used the MARCS model spectra, which were introduced in 2008 (Gustafsson et al. 2008) The MARCS spectra have a flux sampling corresponding to $R \sim 20,000$, which we binned down to $R \sim 1,000$ for comparison with STIS spectra.

The full set of NGSL spectra can be viewed and/or downloaded from the NGSL website on MAST. The website also has documentation giving the details of our processing procedures including aperture-offset corrections and corrections for grating scatter. The URL for NGSL website is:

http://archive.stsci.edu/prepds/stisngsl/http://archive.stsci.edu/prepds/stisngsl/.

4. Absolute Spectrophotometry with STIS

Ideally, an absolute flux standard would be smooth with no spectral break or strong lines; its spectrum could be reproduced by a simple LTE, plane-parallel model; and its apparent flux would be suited to the telescope/science program. No such star fulfills all these requirements, but low-metallicity stars at $\sim$ 6000 K come close. fFigure 2 shows spectra from the NGSL of low-metallicity, main-sequence stars in the temperature range, 4900-7300 K. It shows that stars like BD $+29^{o}$2091 with its weak spectral features – no Balmer Jump or Calcium-K Break and only weak lines - are among the best flux standards.

Figure 3 compares our (unpublished) estimates of atmospheric parameters with those derived from Elodie (Prugniel et al. 2007) or compiled from the literature (Cenarro et al. 2007) for the MILES spectral library (Sanchez-Blázquez et al. 2006) for those stars in common with stars in the NGSL.

The path toward measuring absolute fluxes to less than 1% is now clear. We recommend adopting the NGSL approach to HST/STIS observations (§2) with the following important exceptions:

- Submit a regular General Observer (GO) proprosal rather than the Snapshot (SNAP) proposal. Observing time for GO programs is allotted in full (or multiple) orbits. Use this extra time to center the star in the slit via the ACQ/PEAK procedure and to take wavelength-calibration spectra at each grating setting.

- Observe the program star using a wider slit, specifically the 52x2E1 slit. The wider slit will transmit nearly all the light of the star, so the flux uncertainty involved with aperture corrections is eliminated.

Data reduction will be simplified compared to the procedures described in §3 because no aperture corrections will be needed, and wavelength-calibration observations will be available. Correction for UV grating scatter, however, will still be needed.

With this modified observing procedure combined with better Hipparcos distances (van Leeuwen 2007) and estimates of color excess, there is even the possibility of deriving the intrinsic flux at the surface of the star, at least for the closer stars.

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