International Workshop on Stellar Spectral Libraries
ASI Conference Series, 2014, Vol. 11, pp 1 – 6
Editors: H. P. Singh, P. Prugniel and I. Vauglin

HST/STIS Advanced Spectral Library (ASTRAL)*

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Abstract. ASTRAL is a *Hubble Space Telescope* Large Treasury Program whose aim is to collect full-coverage ultraviolet (1150–3100 Å) echelle spectra of representative stars of spectral types O–M, with resolution and S/N comparable to the best now obtained routinely in optical observations from the ground. First part of the program – *Cool Stars* – was completed in 2011. Second part – *Hot Stars* – is in progress (2013–2014). Resulting high-level processed UV "atlases" are available from the ASTRAL site:

`http://casa.colorado.edu/~ayres/ASTRAL/`

Keywords : atlases – stars: early-type – stars: late-type – ultraviolet: stars

1. Introduction

In 2004, the untimely failure of UV Astronomy's most important asset – *Hubble* Space Telescope Imaging Spectrograph – forced a period of reflection on UV spectroscopists, who pondered in the ensuing years what might have been done if STIS still had been available, regretting the missed opportunities. Then, in 2009, STIS miraculously was returned to service, thanks to *Hubble* Servicing Mission 4, and once again the UV community had a powerful tool to make good on those musings. To that end, an international team of stellar astronomers banded together to propose a far-reaching effort to fill significant gaps in the existing *HST* UV echelle collection on stars, ultimately to build an Advanced Spectral Library (ASTRAL) – spectroscopic equivalent of a *Hubble* Deep Field – which can be put to many uses and will have enduring value.

The initial installment (ASTRAL *Cool Stars*), was awarded 146 orbits ("currency" of *HST* observing), and carried out successfully in *HST* Cycle 18 (2010–2011). *Cool Stars* focused on the cool half of the Hertzsprung-Russell diagram, with

*Based on observations from *Hubble Space Telescope,* collected at Space Telescope Science Institute, operated by Associated Universities for Research in Astronomy under contract NAS5-26555.

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its convection-driven magnetic activity, and nonclassical high-energy far-ultraviolet (FUV: 1150–1700 Å) emissions. This initial segment of ASTRAL has been described by Ayres (2013). The second part – *Hot Stars* – not surprisingly focuses on the warm side of the H–R diagram, dominated by strong winds among the more luminous O-types, and remarkable chemical and magnetic peculiarities further down the MS toward late-B and early-A. Both programs naturally also have an interstellar medium (ISM) component, because any UV-bright target can serve as a background source against which to probe the gas between the stars. ASTRAL *Hot Stars* was awarded 230 orbits, largest program in current Cycle 21 (2013–2014). Observations began in 2013 September and to date (early December), five of the 21 targets have been completed. Here, the guiding philosophies of the overall ASTRAL Program are described, with emphasis on the new *Hot Stars* episode.

2. ASTRAL *Hot Stars* program

Our objective was to capture full-coverage UV spectra (1150–3100 Å), at echelle resolution (R ~30,000–100,000) and high signal-to-noise (S/N>100), of representative early-O to early-A spectral types, both Main sequence and evolved stars, fast and slow rotators, as well as specialized types of chemically peculiar and magnetic objects.

WHY UV? The satellite UV (1150–3100 Å) is highly prized. It captures processes as diverse as fluorescent pumping of cold 100 K molecules in star-forming clouds; 1000 km s^{-1} broad P-Cygni profiles of early-type winds; and ultra-narrow (few km s^{-1}) absorptions from the thin interstellar gas. Resonance multiplets of H I, C I, O I, Fe II and Mg II, among others, fall in this interval. Highly-ionized species are found here as well, including important Li-like doublets of C IV and N V. Stars blandly similar in the visible, can be strikingly different in the UV.

WHY HIGH RESOLUTION? High spectral resolution helps decipher starlight in many ways. It can disentangle close blends; readily captures kinematic signatures like Doppler shifts, asymmetries, and broadening; and boosts contrast of weak features. The undeniable advantages of high-resolution UV spectroscopy have led to multiple generations of increasingly sophisticated instruments in space (although, sadly, STIS might be the last of its kind for some time to come).

WHY HIGH SIGNAL-TO-NOISE? High S/N goes hand-in-hand with high spectral resolution. High S/N boosts the precision of wavelength measurements ("kinematic decoding"), and is essential to distinguish weak features; not only trace stellar or ISM or species, but also subtle profile distortions, such as faint, high velocity discrete absorptions in P-Cygni line shapes. Based on our collective experience, we believed that S/N$\gtrsim$100 would have especially high scientific impact. This is attainable by STIS with careful observing practices.

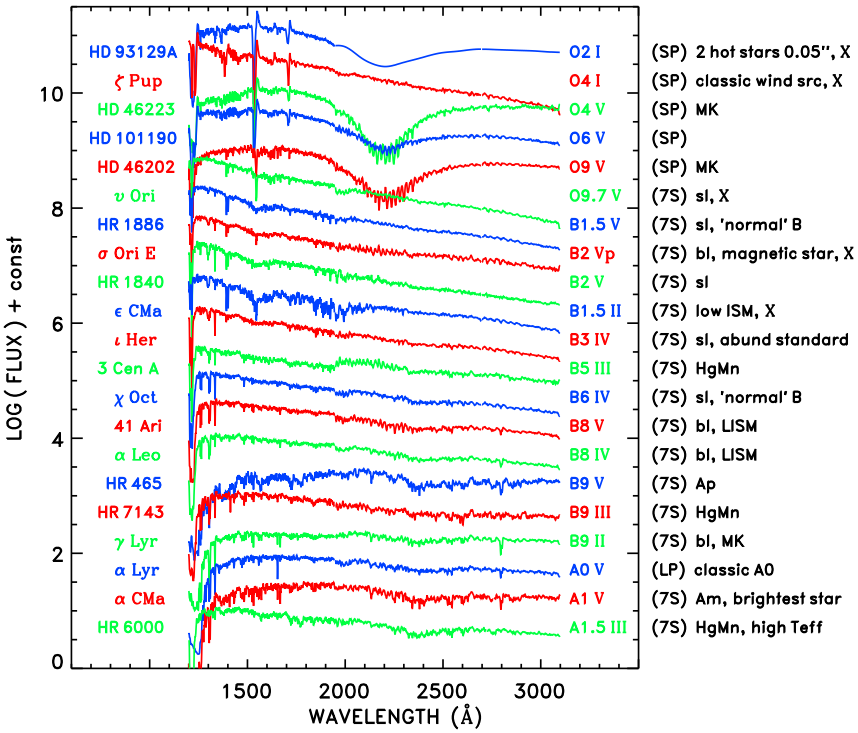

Figure 1. *IUE* UV spectra of ASTRAL *Hot Stars* targets. These low-resolution traces smooth over much of the intrinsic spectral structure. Note prominent 2200 Å bump (ISM reddening) in several of the O stars. Parenthetical notes at right indicate specific observing strategies (as illustrated in Fig. 2, below): **SP**= 6 orbits; **7S**= 12 orbits; **LP**= 20 orbits. Other Notes: "**X**"= X-ray grating spectrum; "**MK**"= from MK standards list; "**sl**"= sharp-lined; "**bl**"= broad-lined.

3. Target selection

Hot stars are so UV-bright they can be seen easily by STIS over great distances. In principle, there is no shortage of potential candidates for a survey like ASTRAL *Hot Stars,* literally hundreds. However, many early-type stars in fact are *too bright* for STIS, triggering over light conditions on the MAMA detectors. The high global count rates can force a switch from the normal clear echelle slits to a special set of neutral-density filtered apertures. The only "supported" such apertures are ND=2 and ND=3. Consequently, if a target just barely violates the camera bright limits, and the ND2 slit must be used, the exposure would have to be ∼100× longer to achieve the same S/N as a "safe" target just under the limit. Since STIS requires between 3 and 9 echelle settings to cover the full UV band, depending on the desired resolution (medium-resolution [M modes]: 30,000–45,000; or high-resolution [H modes]: 110,000), it is possible that a given object would have most settings under the limit, but one of them might be over, exacting a large penalty in overall observing time for that target.

To overcome the dilemma, we carried out a program in *HST* Cycle 19 to validate a set of three intermediate ND-filtered slits that were "available but not supported" (meaning they were not sufficiently well calibrated for general use). The NDs are 0.6, 1.0, and 1.3, nicely filling the gap between the clear apertures and ND2. One issue with these slits is that they are 31″ tall; compared with the normal short (0.2″) echelle slits. The concern was that the tall slits might affect the cross-dispersion profile of the echelle orders, leading to interference between adjacent orders, enhanced scattered light, and/or loss of resolution. Test exposures of the bright source Vega, however, assuaged these fears. The wavelength-dependent attenuation of the intermediate ND slits was calibrated using the hot-WD G191B2B.

We then developed a scheme to "qualify" targets via count-rate simulations based on synthetic spectra, analogous to STScI's Exposure Time Calculators. ASTRAL team members, experts in their respective fields, contributed initial candidate targets, about a hundred in all. These were vetted through the feasibility tool, and those that passed initial screening, about forty, were subjected to a more rigorous assessment. This was done by building a consensus *IUE* spectrum (Fig. 1) and passing it to a more sophisticated exposure "robot," which selected the optimum slit (ND, or not) to keep the global count rate of each echelle setting as high as possible (which positively impacts S/N), but below the bright limit. Team members then debated the merits of the surviving candidates. Ultimately we converged on a final group of 21 targets that: represent spectral classes from early-O to early-A; contain examples of hot-star exotica, like HgMn and Ap; and include both sharp- and broad-lined cases. Among the final targets (see Fig. 1) are iconic Vega, Sirius and Regulus; as well as historically important objects like classic O-star wind source ζ Puppis.

4. Observing program

We devised two generic observing programs: *Seven Samurai* (**7S**), designed to achieve highest practical resolution throughout the UV, for studies of sharp-lined stars and any object, sharp-lined or not, which might be useful for ISM purposes; and *Short Program* (**SP**), which exclusively utilizes the medium-resolution echelles, applied to the distant reddened broad-lined O stars, of less interest to ISM research.

7S trades resolution against wavelength coverage where the effective STIS sensitivity for an early-type SED is low, in order to minimize the number of orbits needed per target. **7S** makes use of the following settings— E140H-1271 and E140M-1425 in the FUV, to ensure full coverage in at least M-res, but H-res below 1360 Å where important stellar (and ISM) features fall. E230M-1978 captures the short NUV (1700–2350 Å) at 30,000 resolution, adequate for most analysis purposes. The long NUV (2350–3050 Å) is done exclusively H-res: E230H-2463 to overlap adequately with the E230M; E230H-2513 to extend to the important 2600 Å region where key ISM absorptions are found; E230H-2713 to overlap with H-2513 at 2600 Å but also cover the important 2800 Å ISM interval; and finally E230H-2912 to overlap at 2800 Å

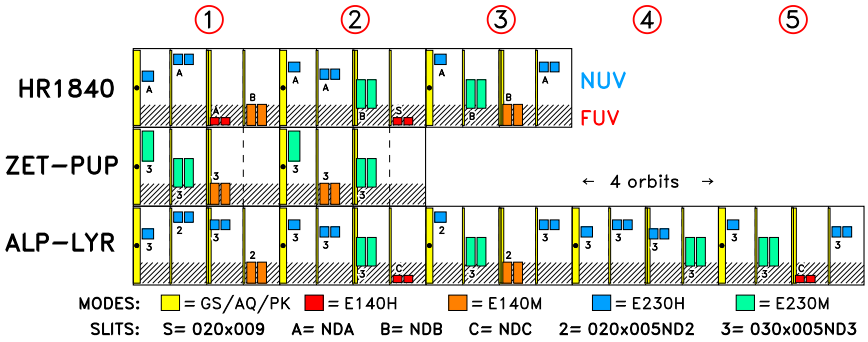

Figure 2. ASTRAL *Hot Stars* observing strategies. Tall rectangles represents 96 minute *HST* orbits; 3–4 such orbits constitute a "visit" (encircled numerals). Colored rectangles indicate echelle settings; vertical extent is wavelength coverage: shorter symbols are H-res settings, taller are M-res; horizontal extent is exposure duration. Lower hatched zone is FUV (1150–1700 Å); upper clear band is NUV (1700–3100 Å). Broader yellow strips are initial target acquisition and first target-centering "peak-up;" narrower yellow stripes are second peak-up later in visit; thin yellow lines are Guide Star re-acquisitions. Only part of each orbit is useful, owing to Earth-block. Optimum echelle slits (target-dependent) are marked according to legend. Upper panel illustrates ***Seven Samurai*** ("**7S**"): 2 M-res echelle settings plus 5 H-res, requiring three 4-orbit visits. Middle panel is ***Short Program*** ("**SP**"): exclusively M-res; two 3-orbit visits. Bottom panel is ***Long Program*** ("**LP**"), special case for Vega (five 4-orbit visits). Observing strategy is designed to ensure accurate wavelength scales, preserve radiometric precision, and suppress detector fixed pattern noise.

while extending out to the atmospheric cutoff beyond 3000 Å. **SP** makes use of E140M-1425, E230M-1978, and E230M-2707, all prime M-res settings.

Example observing scenarios are depicted in Fig. 2. Full-orbit exposures (in orbit 2, and beyond) are split into pairs of sub-exposures, to address spectral drifts. A second peak-up in orbit 3 maintains target centering (essential for the narrow ND slits). The sequences are arranged so that each setting has at least one exposure immediately following a peak-up, for best wavelength and photometric performance. Finally, each grating setting is slotted into at least two separate visits: echellegrams taken in different visits will, in general, fall on slightly different sets of pixels, and thus experience different "fixed pattern noise" (FPN: pixel-to-pixel sensitivity variations). When two such spectra later are combined, FPN is suppressed, allowing the S/N>100 expected from counting statistics, in principle, to be realized in practice. An additional source of FPN reduction is smearing by Doppler compensation for *HST* orbital motion. A third type of FPN suppression occurs where adjacent settings overlap.

Famous solar-neighborhood A0 star α Lyr (Vega) was judged an important target (e.g., zero point of photometric scales; rapid rotator seen pole-on; possible X-ray source), even though its feasibility was below standard in two of the NUV settings.

We devised a "Long Program" (**LP**) for Vega, still utilizing the **7S** settings, but adding six orbits (20 total) to boost S/N in the two under-performing intervals.

5. Constructing the Atlases

A number of processing steps are performed to transform the raw STIS echellegrams into finished atlases. First, the `calstis` pipeline flatfields the raw images, traces the counts in the echelle orders, subtracts a smoothed interorder background, performs a scattered-light correction, assigns wavelengths, and radiometrically fluxes the spectra. Then, a custom post-processing scheme applies a higher-order wavelength correction (see Ayres 2013), and splices the individual echelle orders into a coherent 1-D spectral tracing. Next, independent observations in the same setting (e.g., sub-exposures) are registered by cross-correlation and coadded. Finally, all of the setting-specific spectral segments are spliced together, employing a bootstrapping scheme to optimize the accuracy of the final wavelength scale, and ensure relative precision in the fluxes across the full UV band. The final UV atlases, as well as the individual spectral segments from each level of processing (say, for variability studies), are available from the project website (as noted in the abstract). The ASTRAL material is intended to support diverse investigations, for years, if not decades, to come.

Acknowledgements

I thank the more than thirty Co-Investigators, from all over the world, who have participated in the ASTRAL Project over *HST* Cycles 18 & 21. This work was supported by Guest Observer grants 12278.01-A and 13346.01-A from STScI.

References

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