KOSMOS Reduction Report

James Davenport (UW)

KOSMOS was used on 2021-Oct-07 B-half for initial science testing. We targeted 2 standard stars and 2 M dwarfs, using the 2.0 arcsecond slit, and taking numerous calibration images to characterize the stability and performance of the instrument from a science-user standpoint. Many thanks to Sarah Tuttle and Russet McMillan for helping observe with KOSMOS during its commissioning phase before it was fully integrated into TUI.

The data was processed using an Alpha version of the PyKOSMOS reduction software. The conclusions and recommendations are the opinion of J. Davenport alone.

Executive Summary

The instrument overall performs exactly as expected for a low- to mid-resolution spectrograph on this telescope. Reduction is quite similar to what users would expect from e.g. DIS. I did not measure the throughput, but exposure times were essentially as expected. The wavelength solution is quite linear for both red/blue grisms, and distortion in both wavelength and spatial direction is completely acceptable.

The internal arc lamps (Neon and Krypton) are quite useful for quick wavelength calibration, and users should likely take arcs at every pointing. Wavelength calibration does appear somewhat unstable, though more testing is needed to determine if this is instrument sag/shift or grism alignment when shifting between modes (red/blue or low/center/high). For all blue grism modes (and perhaps red-low) the truss Helium lamp is very useful for anchoring the wavelength solution. Adding an internal Helium lamp would be a welcomed upgrade. The internal Argon lamp was not tested.

Jumping between grism modes is quick and allows users to take both red/blue data for a given target. However, I again emphasize the need to take internal arc lamp images for every pointing & grism mode. Reduction pipelines should strive to make regular updates to the wavelength calibration effortless.

The internal quartz lamp has a strange reflection feature and seems unusable at this time. Users should instead take Bright Quartz flats from the truss lamps until this is resolved. Since long exposures (with mirror covers closed) are needed, the observatory should consider taking a series of standard flats for users at all grism settings.

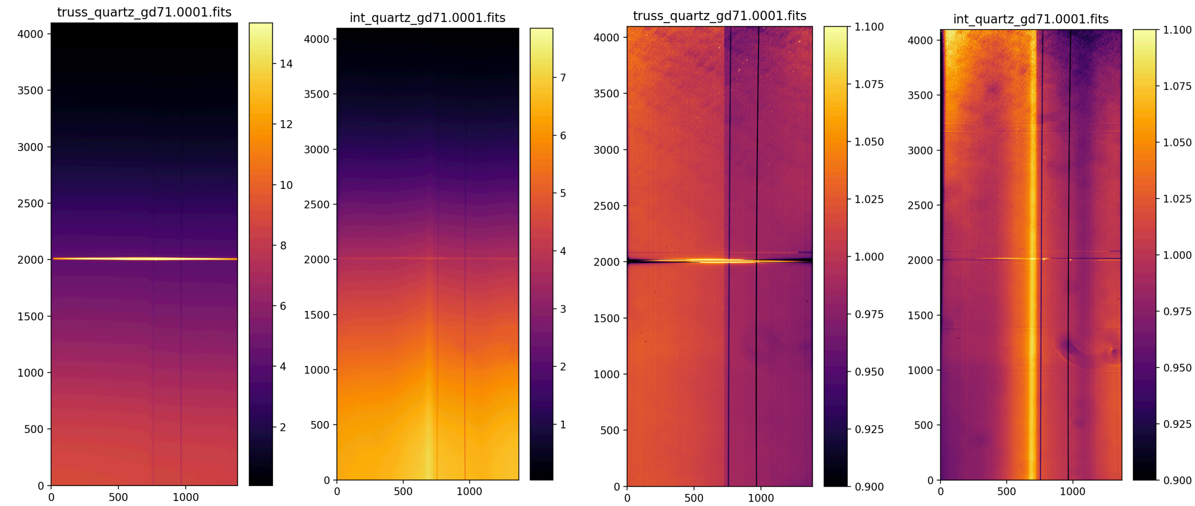
Flux calibration otherwise appears straightforward in the normal way, and calibration of blue/red modes seems possible for most observing modes (provided you remember to take appropriate cals).

The “PyKOSMOS” software needed only minor upgrades to reduce this test data, primarily in dealing with “vertical” images instead of “horizontal” (e.g. DIS).

Quartz Flats

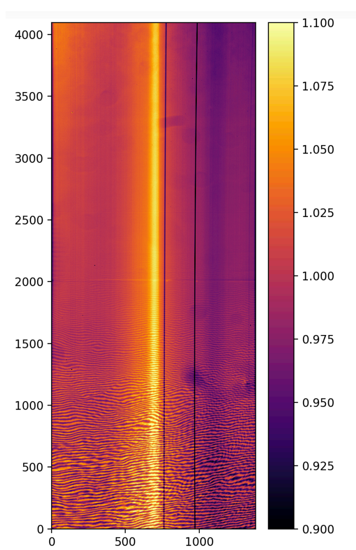
We briefly compared the truss vs internal bright quartz lamp, for use in flat-fielding. Here are examples for the **Blue-Center grism setup**.

- Internal quartz gave peak counts around 45k, with *exptime* of 0.5sec
- Truss lamp bright quartz gave peak counts of 155k with *exptime* of 300sec



Left: flat field images for truss and internal lamps, normalized by the median value of the flat.
Right: flat field images with response function divided out, and normalized by the median value of the flat.

When we divide out the response function (taking the median spectral shape across all columns), the normalized residual shows a few interesting features. Most notably the slit is apparent in the internal quartz image (column ~650). This might be due to strong internal reflections?



We did not test the internal versus truss quartz lamps for any other grism mode, but I do note a similar slit-like reflection feature is present in this example from co-adding 5 internal flats in the Red-Center mode.

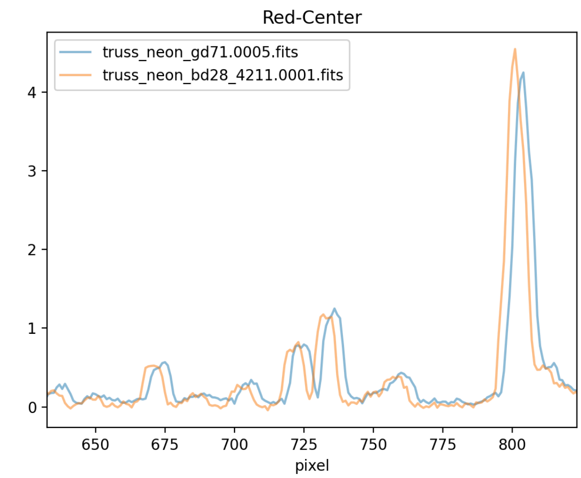
Conclusions:
Truss lamps are strongly recommended for users at this time. While truss flats are considerably slower to take, requiring both longer integrations and closing the mirror covers (per standard operations on the 3.5-m), they can be acquired before/after observing.

Further diagnostics and characterization of the internal quartz lamp is needed for all grism modes.

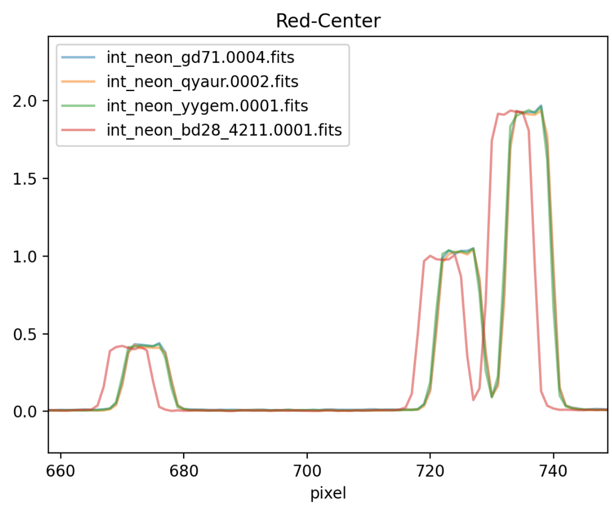
Arc Lamp Stability

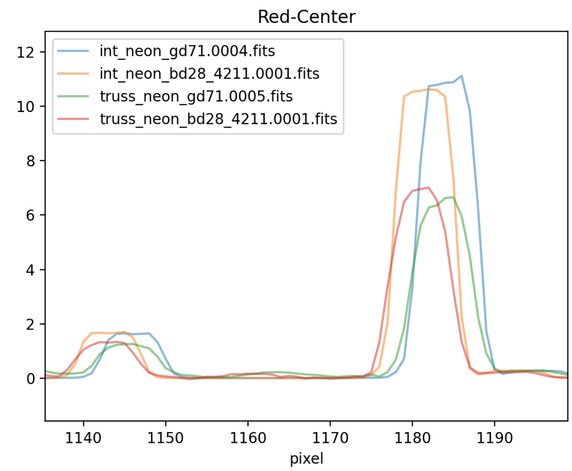
During commissioning reports of significant internal sag were reported, which might result in a variable wavelength solution. To test this we used both the new internal arc lamps and the venerable truss lamps.

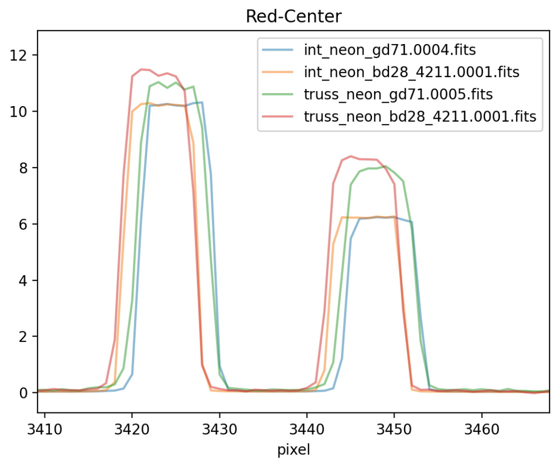
There does appear to be some sag or variability in the wavelength solution at different telescope positions. Here are the truss lamps for two very different pointings. An offset between these two spectra of ~5 pixels is seen. This is consistent across all wavelengths, though a precise shift as a function of wavelength (or row) should be made.



The same effect is seen for the internal lamps. The BD+284211 pointing seemed to have a significantly different grisim position. However, the three other pointings appeared remarkably stable, despite numerous changes to the grism setup.







We can also pair the truss & internal lamps at the same pointings. Thankfully the internal and truss lamps seem to give fairly consistent solutions. I do note, however, the profiles of the internal arc lines are more flat-topped, even for small-amplitude lines (i.e. I don't believe this is a saturation issue). Could this indicate a scattered-light issue?

Conclusions:

- arcs are needed at every pointing due to the possibly variable grism position.
- Internal arcs seem suitably consistent with the truss lamps, and are much faster to take, though they may have scattered light issues giving slightly less precision in wavelength solution. Internal Ne and Kr lamps are recommended at all grism positions (see next section).

Further Testing Needed:

Need to isolate the source of the wavelength instability. Is this in the instrument at different e.g. rotator positions, or is the instability due to the grism position being imprecisely set (or both)?

- Taking data with a fixed grism position but at very different sky/rot positions.
- Taking data with fixed sky/rot position, but changing and resetting the grism position

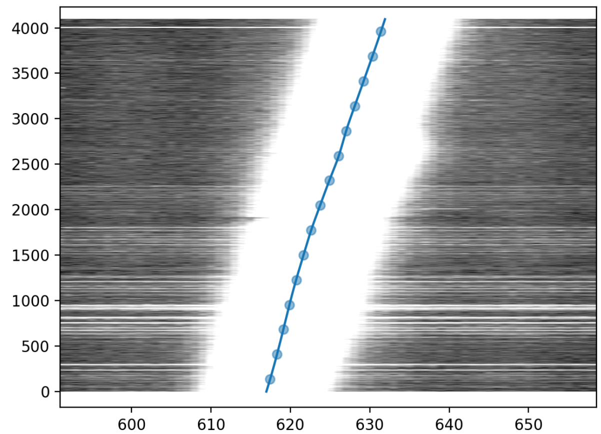
(This testing could be done during day/engineering hours)

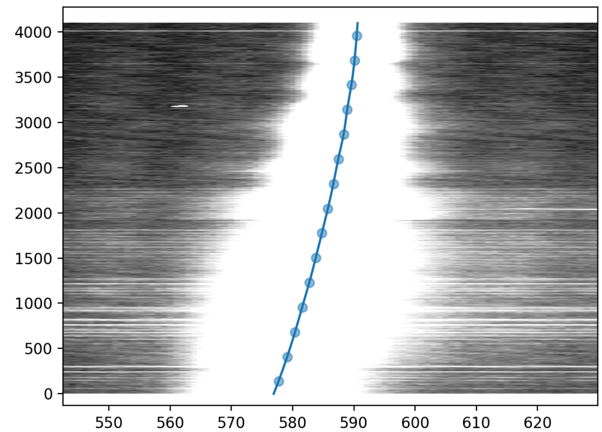
Also good to investigate the cause of the flat-topped line profiles from the internal lamps.

I also noted: The "NEON" keyword in the header did *not* seem to be set when the internal lamp was on. Possible bug in TUI integration?

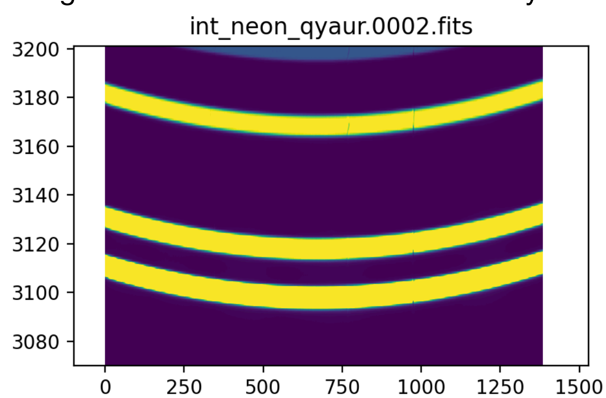
Alignment

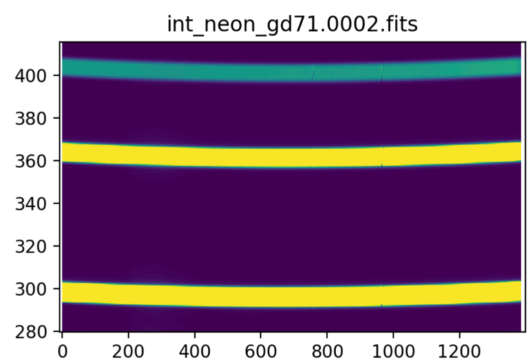
The projected trace of the spectrum is reasonably straight across the detector, shifting in the spatial direction only by ~10pixels across the entire wavelength range. Two examples are shown below for a flux standard in the blue (left) and a M dwarf in the red (right). This seems unremarkable, and comparable to the trace in DIS.





Distortion of arc lamp lines are similarly reasonable. Two examples are shown below for Neon in both red (left) and blue (right) modes. Both have ~10pixels of bend, which is again qualitatively similar to the performance of DIS, and very usable for simple “boxcar” extraction of point-source objects. Of course, high flux precision (or extended source spectroscopy) requires more sophisticated de-projection and extraction techniques, but typical users will find tracing and extraction with KOSMOS easy.





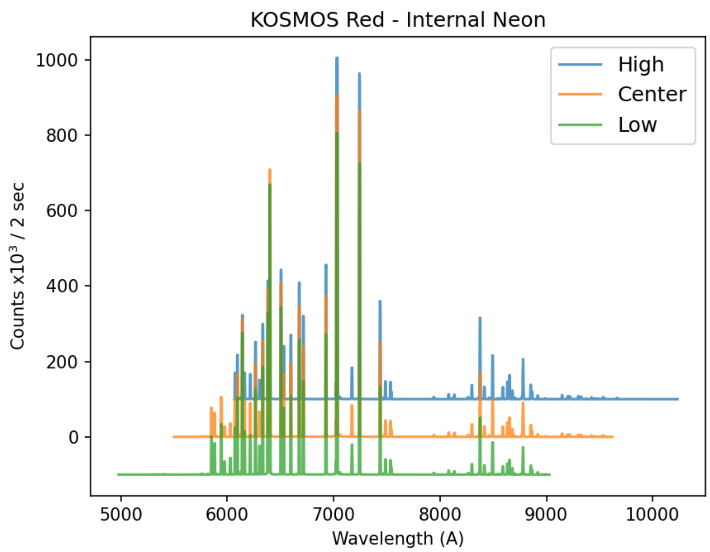
Conclusions:

- Projection/distortion in both wavelength and spatial dimensions is exactly as a typical user would expect for a low- to mid-resolution, long-slit spectrograph like KOSMOS.

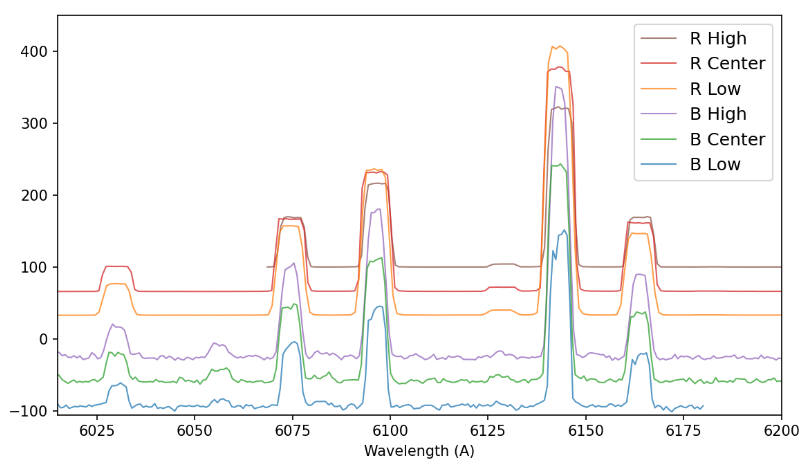
Wavelength Calibration

The wavelength solution in both red and blue sides is quite linear, though a 3rd-order polynomial (or better still, a spline or Gaussian Process) is needed to produce reasonable fit. Wavelength calibration for the Red side can primarily be accomplished with only the internal Neon lamp using very short exposures. Blueward of ~5800 angstroms (especially important for the Red-low configuration, but also notable at Red-Center) the lack of Neon lines makes the calibration a bit difficult. Using the internal Krypton lamps allows use of Kr I features at 5562.2253, 5570.2894, and 5870.9160 to help anchor the calibration.

Similar issues arise at the red wavelengths, though small Neon amplitude features can be seen out to 9534.167. Argon lines at 9122.97 and 9657.78 would be helpful. There are many Kr I features[1] past 9700 that might be useful, and using internal Krypton lamp is recommended.



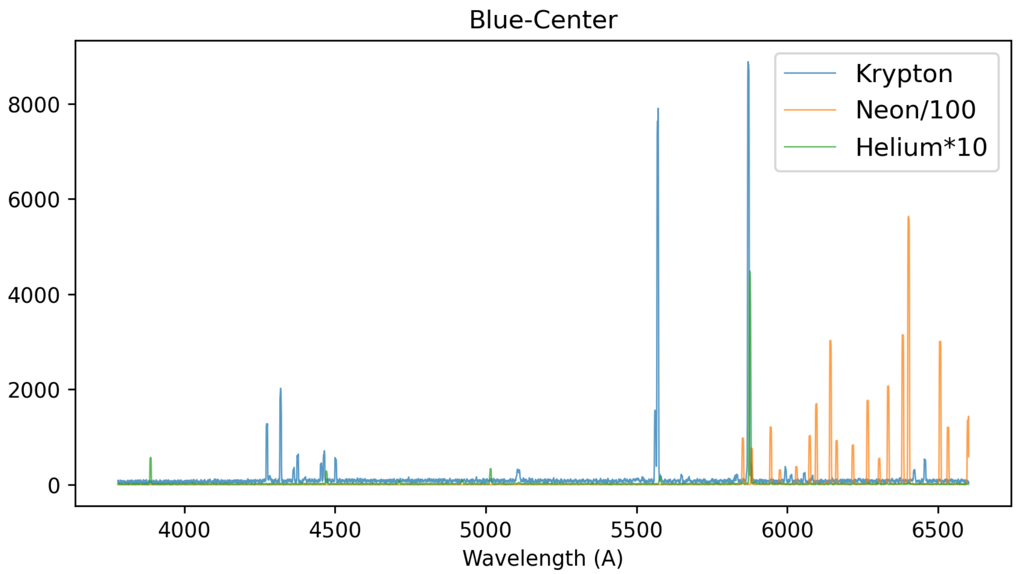
There is a nice region centered around 6100A with ~4 strong Neon lines that is accessible at *all* grism configurations. Neon is therefore always a good bet for doing frequent wavelength calibrations (e.g. at every pointing).



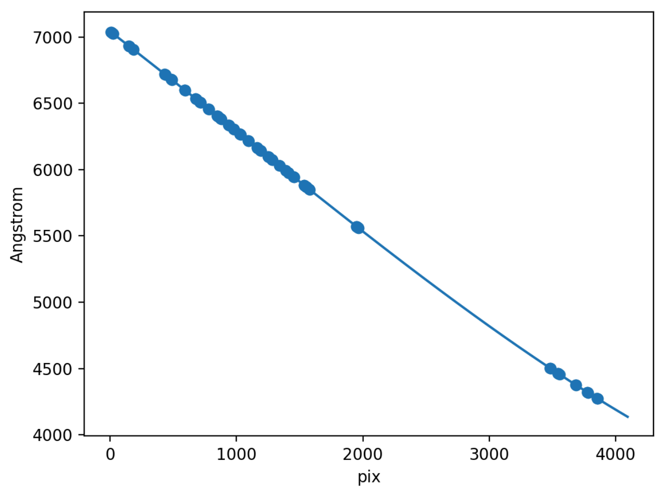
---

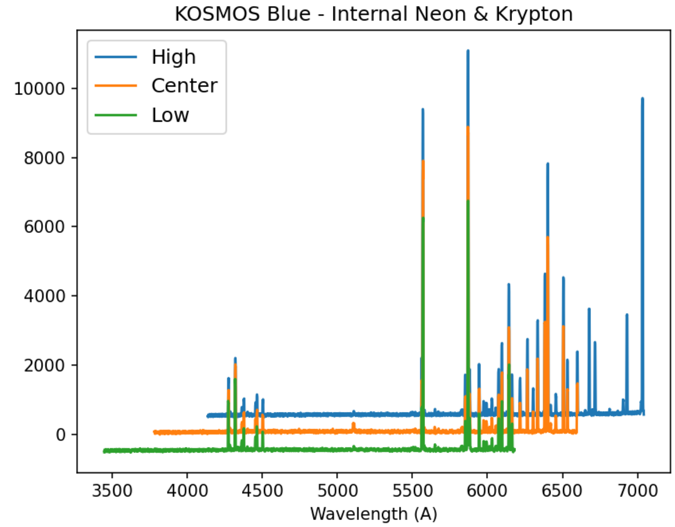
[1] https://physics.nist.gov/PhysRefData/Handbook/Tables/kryptontable2.htm

Wavelength calibration in the blue is somewhat more difficult, and a combination of lamps is always required. The internal Krypton lamp gives several excellent lines around 4300. Unfortunately the intensity of these Krypton lines are much lower than the internal Neon lines, and separate images is probably best for robust calibration. However, at 2 seconds (the exposure time used for Neon), the small Kr I lines are visible, and a combined KrNe exposure is likely sufficient for checking wavelength stability.

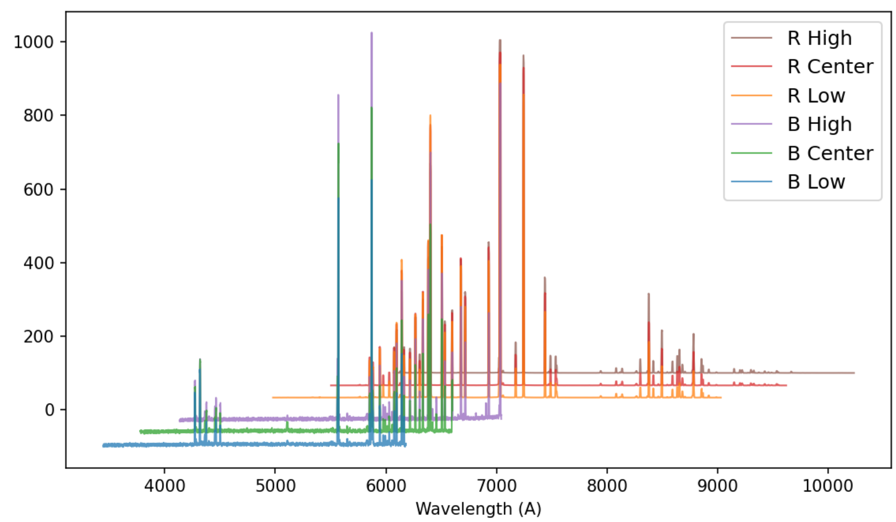


To reach the bluest parts of the spectrum, small Helium lines from the Truss lamp are extremely useful. These lines (seen above) are very low amplitude. Though the dispersion across the detector is relatively linear, a 3rd order polynomial *at least* is required to fit the solution (see below for an example wavelength solution at Blue-High). With testing and robust wavelength solution templates it may be possible to skip taking the He lamp exposure entirely, but it's probably a good idea to include.





Even just using Neon and Krypton, reasonable wavelength solutions are possible for the entire blue range (above). These lamps should be taken at all blue positions as well. Overall KOSMOS reaches from ~3800 angstroms to around 1micron. Red-Low is an excellent default position using NeKr for wavelength calibration. I naively computed a mean spectral resolution *per pixel* of $\lambda_p / \Delta\lambda_p \approx 7000$ in both red and blue modes.



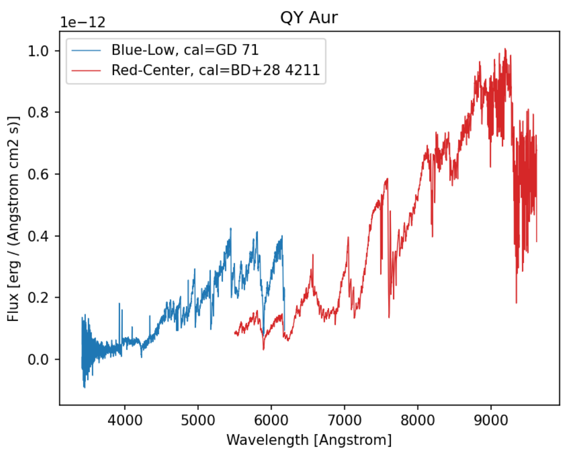
Conclusions:

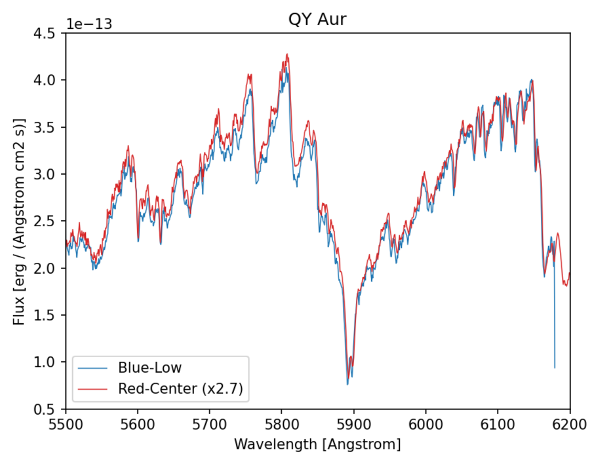
- Take internal Neon and Krypton lamps at all grism configurations.
- 2 seconds for NeKr is sufficient, and for most cases they can probably be taken together
- Adding the Truss Helium (or possibly Argon) lamp helps a lot in the blue, especially for Blue-Center and Blue-Low
- Rapid (automated?) spot-checking of the grism position can be done quickly with Neon using the features always accessible around 6100 A.

Flux Calibration

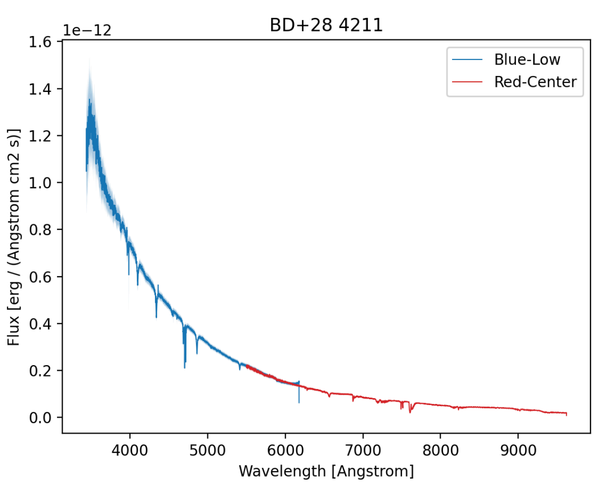
We observed two flux standards and two science targets (M dwarfs) during our test observations. Full reduction, extraction, wavelength and flux calibration was carried out for the science target, QY Aur in both blue and red modes (below). Unfortunately for the red-center mode (the only red mode obtained for this target), the planned standard star (GD 71) was off the slit. This was simple user error, since KOSMOS was not fully integrated into TUI and observing was quite difficult, and no recommendations are needed. Instead another flux standard (BD+28 4211) from the same grism mode was used. As below (left panel), the flux calibration is not especially good for for the Red-Center data. Since the flux standard was taken several hours earlier and at high airmass, the spectrophotometric solution is clearly not good enough.

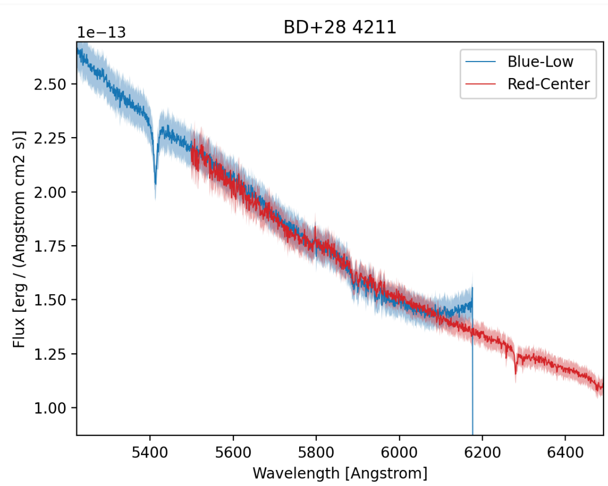
However, when we adjust the Red-Center data to match the overlapping region of Blue-Low (right panel), the wavelength calibration is reasonably close, and the amplitude of the atomic line and molecular band features are well matched.





For completeness, I also fully reduced the Blue-Low data for BD+28 4211. Using the spec50cal IRAF data to generate the sensfunc for this target in both red and blue modes, the flux-calibrated spectrum below looks very reasonable.





Conclusions:

- Flux calibration seems possible for both red and blue modes, and can likely be combined.
- A more careful test would be useful… but no concerns at present.