ARIES and the HeI 1.083 µm line

or

Lies, Damn Lies, and the Grating Equation

As one of the very few cross-dispersed infrared echelle spectrometers on the planet, ARIES provides a uniquely powerful observing mode: with its incoming 2048x2048 Hawaii-2RG detector, much of the 1-5 µm spectrum can be simultaneously recorded at high dispersion ($\lambda/\Delta\lambda \sim 3\times10^4$ or higher). Only beyond 3 µm must the grating be tilted to a secondary setting in order to fill spectral coverage gaps.

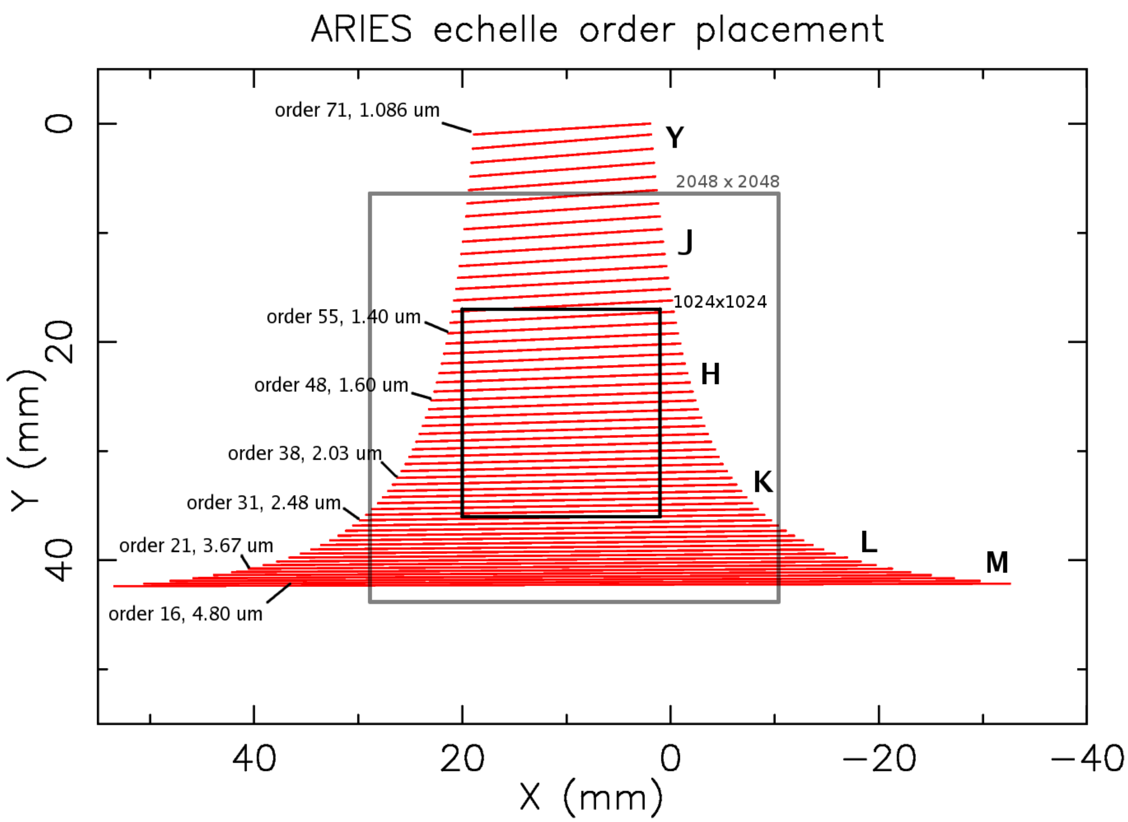

Figure 1: Hawaii-1 and Hawaii-2RG footprints on ARIES' cross-dispersed echelle grating orders. Approximately 1500x1500 pixels of the new array are expected to be unvignetted using the existing optical elements using the f/5.6 camera, and essentially the full array should be usable at f/10.3.

Two grating-related parameters can reduce the optical efficiency with which a particular wavelength may be observed with ARIES, detector quantum efficiency notwithstanding:

- The grating efficiency is sensitive to the off-blaze dispersion angle (Figure 2). As the highest orders have small free spectral range (λ/n), the grating is operated quite close to the blaze angle for Y/J/H/K bands. Only in L&M bands is the off-blaze grating efficiency of special concern.
- For any particular order, the free spectral range cutoff will place certain wavelengths at the end of one order and at the beginning of the next. While in principle no light is actually lost (at worst, the spectral line is observed in two places), the derived SNR is expected to be lower due to the accumulated read noise and/or background variance of many more pixels.

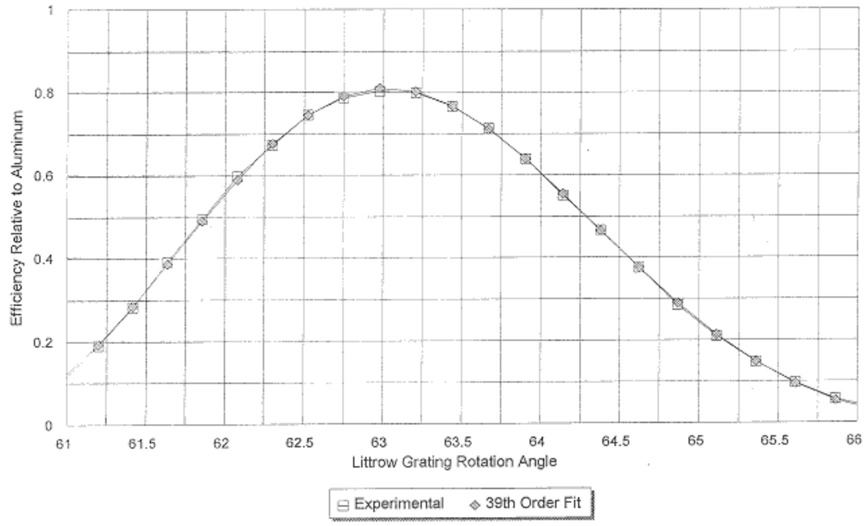

Figure 2: Plot of grating efficiency versus dispersion angle for ARIES' echelle grating, derived from Richardson grating master MR149 (d → 23.2 l/mm)

The HeI 1.083 µm line appears to fall into the second category. This is not a special case; indeed, several lines in the Hydrogen Brackett series (n=17-4, 15-4, 12-4), the H_2 1-0 S(0) and S(2), and ^{12}CO overtone R-branch low-J lines... all fall near the edges of their respective orders (Figure 3).

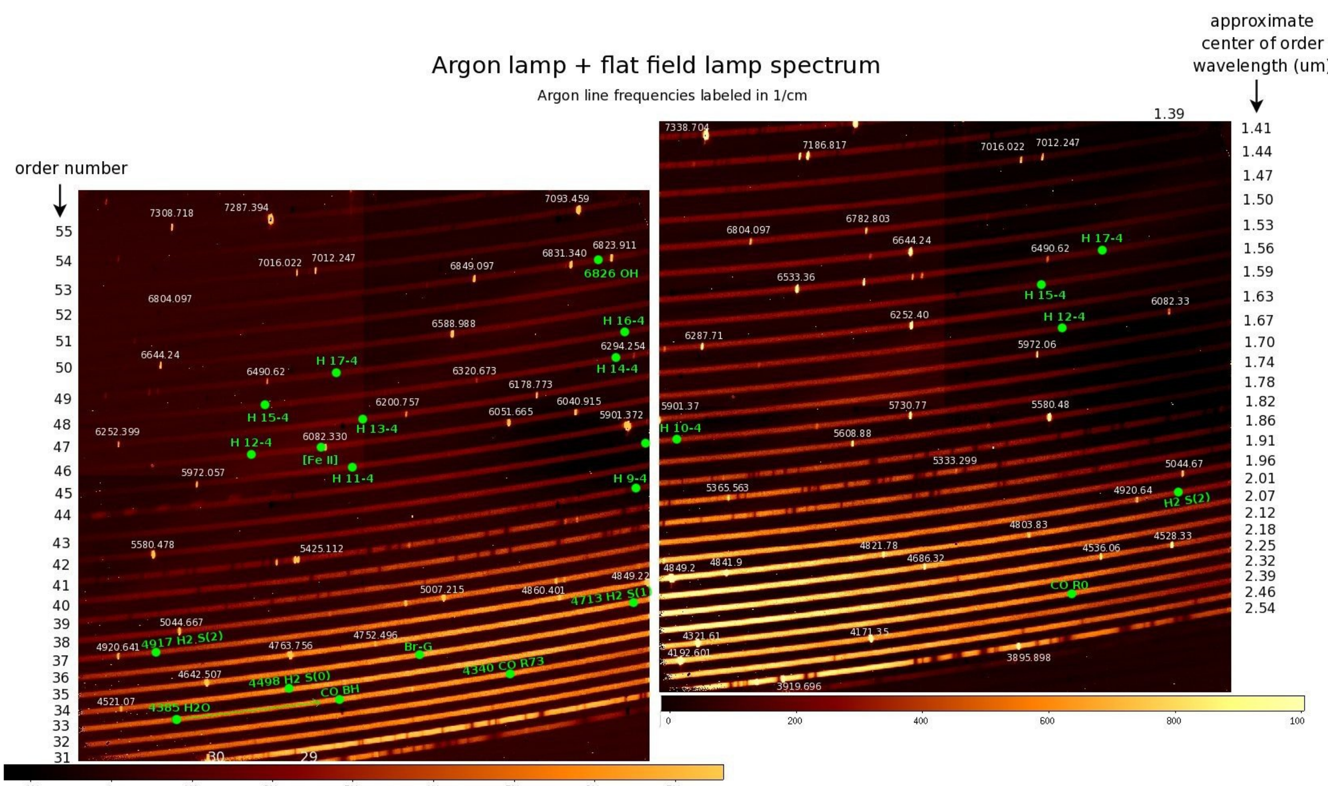

Figure 3: Observed ARIES echelle spectra in the JHK bands of a flat field lamp with the infrared spectrum of Argon superimposed.

There is a problem however. By comparison with Figure 1, in which the expected wavelengths at the beginning of an order are noted, *there should be no trouble with the HeI line*. Order 71 has 0.015 μm free spectral range, and 1.083 μm lies near the order center. There should be no significant loss of efficiency. *Worse, the observed center of every single order appears to be offset from that expected.*

This implies a discrepancy between what is observed and what is predicted by simple application of the standard grating equation: $n\lambda = d\,(\sin\alpha + \sin\beta)$, where n is the echelle order, λ the wavelength, d is the grating ruling separation, and α and β are the incident and dispersion angles relative to the grating normal.

There are few escapes from such a simple expression. The double-pass optical design of ARIES' echelle mode requires operation very near Littrow mode, i.e. $\alpha = \beta$, otherwise the dispersed spectrum would not retrace its path to the grating selection mirror and onwards to the three-mirror reflective camera. The grating itself has the correct ruling spacing, else the observed dispersion would be different than that expected.

The standard grating equation however assumes that the incident & diffracted rays lie in the same plane as the rulings and blaze. However, it is known that for operation in the canonical JHK bands, the grating must be tilted in the orthogonal direction by 7.5 degrees, and operation extending to Y band doubles this incidence angle to 15 degrees. This modifies the grating equation predictably:
$n\lambda = d\,\cos\varepsilon\,(\sin\alpha + \sin\beta)$, where ε represents the out-of-plane angle.

For a blaze angle of 63.1°, grating tilt of ε =7.5 degrees, the following order centers are predicted, in comparison to ε=0, directly compared to the wavelength solutions of Figure 3. The out of plane solutions are essentially perfect.

Order #	λ_{center} (μm), ε=0°	λ_{center} (μm), ε =7.5°	Observed (μm)
30	2.563	2.541	2.542
33	2.330	2.310	2.309
37	2.078	2.061	2.062
41	1.875	1.859	1.860
46	1.671	1.657	1.658
50	1.537	1.525	1.524
54	1.423	1.412	1.412

And what about the HeI line? At ε =15°, the following behavior is seen in the orders around n=70.

Order #	λ_{center} (μm), ε=0°	λ_{center} (μm), ε =15°
68	1.131	1.092
69	1.114	1.076
70	1.097	1.061
71	1.083	1.046

This is also what is observed; 1.083 µm is indeed split between orders 68 and 69. Order 68 is the one typically used at MMT. Note also that the HeI line shows up in an entirely different order than it would at $\varepsilon=0^{o}$.

What grating angle ε would notionally bring the HeI line back to the order center?

Order #	**ε for λ_{center}=1.083 µm**
68	16.7°
69	13.6°
70	9.6°
71	0°

For the Hawaii-1 array, the simplest solution to try is to increase the off-plane angle, also bringing the *n*=68 order closer to the center of the array (but losing most of J band off the bottom of the array). For the Hawaii-2RG array, the likely best solution is to reduce the off-plane angle to 9.6° to center the HeI line in the middle of order *n*=70.

– CK
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