Considerations for an AO-enabled Faint Object Integral Field Spectrograph for Keck

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January 1, 2022

In order to fully exploit AO with ORCAS, Keck will need a new spectroscopic instrument. Currently Keck has no visible instruments with the required spatial resolution. Keck's NIR instruments OSIRIS, MOSFIRE, NIRC2 and NIRSPEC can obtain spectra in one band at a time, requiring 4–7 set-ups. Thus, while suitable for single emission/absorption line complexes at known wavelength (i.e., known redshift for extragalactic targets), they are inefficient for broad wavelength coverage and/or for targets with unknown redshift. Keck's NIRES slit spectrograph does provide continuous NIR coverage in an Echelle mode, but it's throughput is low, both at the blaze peaks and further when accounting for the blaze function for each order. Exploiting the diffraction limit of Keck requires a very narrow slit, making acquistion of faint targets nearly impossible for slit spectrographs and forcing a compromise in slit width between the bluest and reddest wavelengths. A broadband prism integral field spectrograph (IFS) alleviates these challenges.

As argued in [1] broad wavelength coverage for a faint object spectrograph is essential. As but one example, in order to implement the precise (3% in distance) and unbiased SN Ia twinning method[2], restframe 0.33–75 μm should be covered. For SNe Ia $0.5 < z < 1.7$ this translates to wavelength coverage $0.5 < \lambda < 2.0$ μm. The only class of dispersing element able to cover this broad wavelength range with high throughput is a prism. Prisms are usually used in low resolution of $\mathcal{R} \sim$ 100-200, and indeed low resolution is needed in order to pack the integral field spectra onto a single detector, such as a 4k$\times$4k H4RG. Fortunately, SN classification and use of the twinning method for SNe Ia is able to work at low resolution since SN line disperions are of order 3000 km/s, e.g., requiring $\mathcal{R} \sim 100$. The lines widths for many other classes of transients are similar.

The number of resolution elements needed to span a given wavelength range at a uniform resolution, $\mathcal{R}$, is given by: $N_{\max} = \log_{10}(\lambda_{\max}) - \log_{10}(\lambda_{\min})/\log_{10}(1 + 1/\mathcal{R})$. For $\lambda_{\min} = 0.5$ μm , $\lambda_{\max} = 2.0$ μm and $\mathcal{R} = 100$, $N_{\max} = 139$. Since the resolution is defined such that each resolution element is sampled by two pixels on the detector, the length of these spectra would be 278 pixels. Packing these spectra onto a H4RG with a microlens type IFS allows for 56×60 spaxels over the visible plus NIR wavelength range (see Figure 1) for a total of 3360 spaxels[1]. An image-slicer type IFS would fit a field with 14 pseudo-slits, possibly laid out as 17 columns per pseudo-slit. The net number of spatial resolution elements for such an image-slicer would be about 57344. Constuction of such a slicer might be daunting[2]; a slicer with fewer columns of slits would allow higher spectral resolution. This would help broaden the science use cases, and also better isolate the impact of the strongest OH lines.

While focused on faint object spectroscopy, it may be possible to offer higher resolution in the optical by using a different dispersing element and bandpass filters. This would complement the NIR coverage of existing Keck AO instruments. For example, for $\mathcal{R} = 10000$ a wavelength window of 1.4% would fit in the same footprint on the detector. Around Hα this would be a wavelength window of 92 Å allowing, for example, high spectral and

[1]Closer packing of the spectra provides more spaxels, but at the cost of worse cross-contamination from bright sky lines since the spectra are staggered in wavelength. This is the case for OSIRIS.

[2]For comparison, KWCI has 24 slices, and a single MUSE module has 48 slices

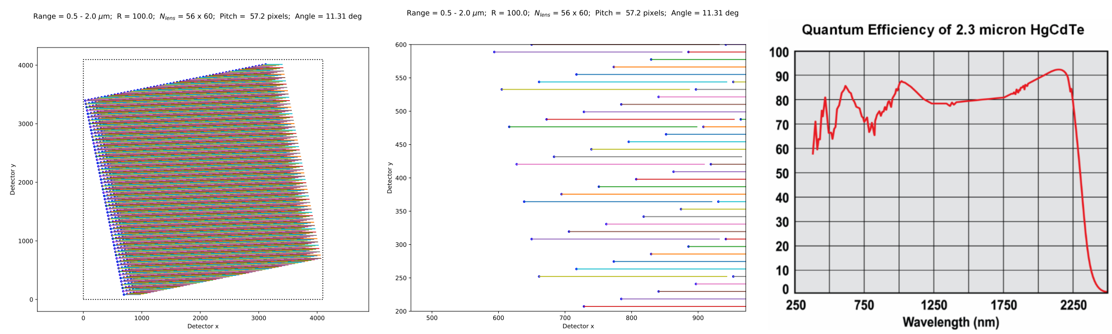

Figure 1: Example layouts of IFS spectra for a microlens array dispersed onto a H4RG detector. The left two plots are for $\mathcal{R} = 100$, This pair shows the full field and a zoomed field, respectively. The right-most panel shows the QE curve for an HxRG detector with the epitaxial layer removed.

spatial resolution of AGN narrow and broadline regions. This would require custom filters centered around each spectral region of interest, but the filters would be small and therefore inexpensive. For optimal performance for different lines, several different gratings would be desirable. Again, this mode is not required, but might be of interest to a broader Keck community than only those interested in faint object spectroscopy.

In the same spirit of mulit-purposing as much of the optics and the detector as possible, the foreoptics could be used to select a few discrete angular scales on which the image segmentation optics would sample the telescope focal plane. The observer could trade FoV for spatial resolution, or even perform a series of observations at different scales. OSIRIS offers this approach, and LIGER will too, so the concept is well established.

The faint-object science case will want to take full advantage of the sky suppression by Nyquist-sampling the PSF beyond $\sim 1\,\mu$m in order to optimally weight the signal relative to the sky. A field magnifier that sets the scale at 10 mas per spatial resolution element would provide a field of 0.56×0.60 arcsec for $\mathcal{R} = 100$ for a microlens IFS. This provides a sufficiently large FoV for the faint-object science case — allowing for errors in target coordinates and acquisition while still encompassing the AO PSF. Other science cases may require a different range of FoV and spatial samplings; for example, study of dual/triple AGN requires a 3×3 arcsec FoV, which for the 56×60 microlens IFS could be covered with sampling of around 50 mas per spatial element. If large enough, an image slicer would provide as large a field while maintaining Nyquist spatial sampling. A small ADC would be required, given such narrow FoVs and the very broad 0.5–2.0 μm wavelength range.

Of course the numbers here are notional; exact values would be required for a true preliminary design. Even so, these simple geometry arguments show that the spectrograph requirements for faint object spectroscopy can be met. In particular, using this geometry it has been shown that simple tranmissive optics can provide low aberration over the full H4RG detector. The optical path length of the spectrograph is only about 1.5 m, leading to a compact instrument.

In summary, ORCAS will enhance Keck AO to a level that merits the construction of a custom supporting instrument for faint object spectroscopy. As sketched-out here, such a spectrograph could be relatively simple, efficient, and compact.

References

[1] Aldering, G. 2021, in Keck White Paper I 2021

[2] Boone, K., et al. 2021, ApJ, 912, 71