KWFI: A UV-Optimized Prime Focus Wide-Field Imager for Keck

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We propose to further investigate a comparatively low-cost UV-sensitive prime focus wide-field optical camera, termed the Keck Wide-Field Imager (KWFI). The main aims of KWFI are to exploit the superior UV transmission on Mauna Kea (down to ~2900Å) and the aperture of Keck to meet the needs of a large number of science cases requiring very deep, wide-field imaging. The Keck telescopes were originally designed with a prime focus wide-field imager as a key facility instrument. No UV-optical space-based telescopes or 8m-class UV-sensitive wide-field imagers are proposed for the foreseeable future. The fast \( f/1.75 \) focal ratio of the Keck telescopes can achieve up to ~1 degree diameter field of view with good image quality from ~3000Å–10000Å, with or without, an atmospheric dispersion corrector. The proposed simple and high-throughput 4-element optical design, and the use of a retired spare secondary housing, keep the cost low and performance high. KWFI has strong synergy with TMT, JWST, and upcoming NASA space missions and provides a unique, and much needed, blue wide-field imaging capability for the Keck community.

Overview

The KWFI concept is driven by the increased science demand for wide-field astronomy. The original Keck telescope design included a 30’ x 30’ (dual-arm) prime focus imager, designed by Harland Epps, as a core facility instrument (Nelson, Mast, & Faber, (1985) Keck Observatory Report 90). In our similar 0.707-degree diameter design, the optical elements have a 1-meter diameter primary lens, comparable to the Canada-France-Hawaii Telescope (CFHT) Megacam. The entire unit fits well inside a retired Keck f/15 secondary module (Fig. 1). Our design does not extend from the secondary housing, providing proper telescope clearance. The design of the Keck top end is less restrictive to a prime focus camera than other similar telescopes (e.g., Subaru) and can support a 2-ton instrument with dimensions 2 x 3m and ample room for simple filter exchange mechanisms, shutter and filter stowage, etc. KWFI will be well under 1 ton, will fit inside existing secondary modules, and can be exchanged in less than ~3 hours. KWFI can be used on either telescope, but will be planned for Keck II, as Keck I has the deployable tertiary mirror. However, it may be used temporarily on either telescope as it enables science during secondary mirror cleaning or replacement, avoiding costly telescope downtime.

Figure 1. Left: The KWFI optical design and its relationship to the inner limits of the Keck top end socket (shown by the red lines). Right: Spare Keck top end carriage, retired from carrying a chopping secondary.
**Existing and planned 4–8m-class wide-field (≥ 0.5 deg) imagers**

KWFI is expected to reach $m (\text{AB}) = 28$, $5\sigma$ in $\sim 2$ hr ($u$), $\sim 1$ hr ($g$), $\sim 2$ hr ($i$), and $\sim 4$ hr ($i$).

**Subaru Hyper-SuprimeCam** (1.8 square deg): 8.2-m telescope aperture enables $m (\text{AB}) \sim 28$ imaging (but slower than KWFI), no u-band throughput, high-demand instrument

**CFHT Megacam** (1 square deg): 3.6-m telescope aperture makes $m (\text{AB}) \sim 28$ surveys very time intensive (cf. the 6-year CFHT Legacy Survey 4 Deep Fields reach $m \sim 27.5$).

**CTIO DECam** (3 square deg): 4-m aperture and typical site seeing make $m (\text{AB}) \sim 28$ imaging highly time intensive; poor u-band throughput; accesses the Southern Hemisphere

**The Large Synoptic Survey Telescope** (LSST; 9.6 square deg): 6.5-m effective aperture, only half the u-band throughput compared to KWFI, accesses the Southern Hemisphere

- **NOTE:** 10 years of stacked LSST survey images are needed to reach $m (\text{AB}) \sim 28$, $5\sigma$.

KWFI is faster than any wide-field imager and has u-band sensitivity. KWFI has a more compact focal plane (341 mm) than wide-field cameras of similar $A\Omega$ power (*figure to the right*) and is well matched to typical detector pixel sizes ($0.178''$ pixel$^{-1}$). On Keck, LRIS provides two-arm $\sim 5' \times 7'$ FOV imaging capability (but suffers from vignetting). DEIMOS has an optional $\sim 5' \times 16.7'$ FOV optical imaging capability, however, it has no u-band sensitivity and an unusual field shape, making imaging surveys less practical.

**Scientific motivation**

Many areas of astronomical research and discovery rely on deep, wide-field images to understand local to high redshift galaxy and stellar populations and to provide targets for longslit, multi-object, and IFU spectroscopy. KWFI is optimized for the relatively unexplored $< 3500\text{Å}$ regime accessible from Mauna Kea. Blue sensitivity is an area in which Keck has placed a focus and has yielded a unique advantage. Spectroscopic science has been achieved at Keck (with LRIS) down to 3050Å. Deep, wide-field optical imaging has direct relevance with, and is complementary to, TESS and future space-based missions WFIRST and EUCLID.

DUET, a UV survey telescope to be proposed in 2019, will observe in two complementary NUV bands, but relies on ground-based observations in the u-band for important science cases. Finally, KWFI will provide faint, rare targets for JWST, including lensed systems. Here, we briefly summarize several science cases in which deep, wide-field u-band imaging is essential.

**Cosmic reionization:** Star forming galaxies are believed to have been largely responsible for the reionization of the Universe. Escaping ionizing Lyman continuum flux ($< 912\text{Å}$) can only be detected from the ground for galaxies at $z \sim 3–5$ as a result of increased IGM absorption at higher redshift. As a result, studying host galaxy properties and the mechanisms behind the escape can only be done at $z \sim 3–5$, and where measuring the escape of ionizing photons is in the u-band. Ongoing research into other indicators, such as restframe optical nebular emission lines associated with the observed escaping ionizing flux, could enable the inference of escape from higher redshift galaxies. However, the connection and calibration of these indicators is restricted to flux escape measurements and galaxy study at $z \sim 3–5$. 
The escaping ionizing flux that survives to Earth is a small fraction of the non-ionizing UV continuum emitted by galaxies. Consequently, the flux is extremely faint and spectroscopic detection requires very long exposures on 10m-class telescopes and is prime TMT science. However, the escaping flux can be detected and measured with deep, KWFI u-band imaging. In addition, theory and detections to date indicate that the largest contributions may arise from galaxies at the faint end of the luminosity distribution, and that the ionizing flux extends to very short wavelengths (<700Å). As a result, deep u-band imaging (mlim ~ 28–30) is necessary to detect their Lyman continuum flux. The relatively low number density of galaxies with escaping flux, and investigations into the effects of environment, require wide-field imaging.

**Optical counterparts to gravitational wave and fast transient events:** The LIGO/Virgo gravitational wave detection of the binary neutron star (BNS) merger GW170817 opened a new door into multi-messenger astronomy and a large number of facilities are involved in searching and following up gravitational wave events. However, recent observations suggest that GW170817 may not be representative of typical kilonovae. The improvements in LIGO/Virgo sensitivity for operational run O3 this year has detected more distant events that are reaching the limit of what is detectable by many of the smaller aperture telescope search surveys, such as ZTF. Larger aperture telescopes are required to follow their rise and fade and, in the more distant and fainter cases, their detection. In addition, black hole – neutron star (BH-NS) mergers have been detected by LIGO/Virgo, which are expected to produce even fainter kilonova counterparts than BNS mergers and potentially detected to even greater distances.

With further expected improvements in sensitivity, LIGO/Virgo gravitational wave detections will occur at even larger distances, with lower masses and, with the addition of the KAGRA detector in Japan next year, the better localization accuracy will require 8m-class optical searches. Finally, KWFI can perform cadenced accuracy for BNS and BH-NS kilonovae out to z ~ 1, beyond the reach of LIGO/Virgo/KAGRA, to understand their populations, progenitors, and range of properties. These searches are independent of LIGO/Virgo/KAGRA and can be initiated at first light and can be designed as part of other galaxy survey science.

Fast transients include fast radio bursts, x-ray bursts, gamma ray bursts, supernova UV shock breakouts, Type Ia UV bursts from collisions with their companion stars and other rare events. Deep u-band imaging is essential to identify these phenomena and to help model and understand their varied physics. The explosion mechanisms underlying several of these high-energy transients are poorly understood or completely unknown. Extragalactic fast transients are rare and can be found in a single night of deep, wide-field imaging of a few square degrees to probe sufficient cosmological volumes for detection. Fast radio bursts are a unique cosmological probe of the ionized baryon content in the line of sight to the extragalactic events. However, the poor localization by most fast radio burst facilities, and in particular all single dish facilities, mandates wide-field imaging, and their high redshift requires very deep imaging.

**Galaxy selection at z ~ 1.5 – 3.5:** U-band photometry is essential to select z ~ 2 and z ~ 3 Lyman break galaxies (LBGs). Deep u-band helps to remove lower redshift sources from higher redshift LBG samples and improves spectroscopic efficiency. Wide-field imaging enables the study of large-scale structure and the investigation of the most rare, brightest galaxies and the search for valuable lensed systems, whereas deep, wide-field imaging enables the study of LBGs with very faint continuum luminosities, at the interface with the Lyman alpha emitter population. Restframe UV properties and optical kinematics of galaxies at z ~ 1.5–3.5, and their use as background sources to map the intervening Universe are key science drivers for TMT instruments MOBIE and IRIS. In addition, TMT WFOS should be able to obtain LBG spectroscopy to m ~ 27 and redshifts based on Lyman alpha to m ~ 28.
Photometric study of LBGs down to $m_{lim} \sim 28–30$ based on these spectra are needed to understand their connection to DLA and absorption-line system populations.

**High redshift supernovae and the first stars:** Supernovae at $z \sim 2–4$ have been discovered in increasing numbers and superluminous supernovae (SLSNe) can be detected to $z \sim 20$ (the formation of the first generation of stars) using upcoming facilities, including TMT and JWST. SLSNe may be our only probes of the $z > 15$ Universe, as proto-galaxies during that epoch are too faint. Deep u-band is essential to select $z \sim 2–3$ LBGs to monitor for supernovae, a proven efficient technique that eliminates the much larger number of low-redshift transients, and wide-field imaging is necessary to detect these rare events. Pair-instability supernovae are a long-theorized type of supernova resulting from the deaths of very massive ($140–250 \, M_\odot$) stars. They are predicted to occur more frequently at high redshift and in faint, low metallicity systems. Deep, u-band imaging necessary to understand the extreme energies and exotic explosion mechanisms of $z \sim 2–4$ supernovae and, importantly, their far-UV behavior in order to identify supernovae at higher redshifts, where the far-UV is the only wavelength regime accessible, even with JWST (cf., $1700 \, \text{Å} \sim 3.6 \, \mu \text{m} \text{ at } z = 20$). KWFI, together with JWST, will find the first stars in the Universe by finding the first SLSNe and pre-supermassive black holes.

**Lyman alpha emitters at $z \sim 1.5–2$:** Sensitivity below 3700Å opens up a window to very efficient detection of $z \sim 1.5–2$ Lyman alpha emitting galaxies (LAEs) using narrowband imaging, as no lower redshift strong emission lines are present to contaminate the samples. Such research would be unique to Keck, as $z \sim 1.5–2$ LBGs have not been detected in any significant number as a result of instrumentation and atmospheric constraints. Yet, $z \sim 1.5–2$ is a period of rapid change for LAEs and key observations would link $z \sim 1$ LAEs to higher redshifts. Deep narrowband filter imaging between ~2900Å–3700Å is required for detection and wide-fields are needed to detect statistical LAE samples and to perform clustering studies.

**U-band mapping of local galaxies:** The UV is an efficient method of probing low levels of star formation in elliptical galaxies and wide-field u-band imaging enables searches for low-level star formation in the outer regions of nearby galaxies and enhances SED fitting. For example, the Galex satellite has detected ~1 Gyr old star formation at the level of ~1% of the stellar mass in ellipticals and an outer star-forming ring in the lenticular galaxy NGC 2974 has been detected in the UV. For late type spiral galaxies, deep, wide-field u-band imaging reveals the distribution of star forming regions (i.e., young stars) and exotic hot stellar objects, while helping probe the distribution of dust and escaping radiation. The imaging can help resolve the current mismatch (factors of 2-4x) between optical vs. UV star formation rate measurements.

**Globular cluster selection:** The u-band is particularly useful for selecting globular cluster candidates. For example, the metal-poor and metal-rich globular cluster sub-populations are well separated in $(u – i)$ color, as the u-band is sensitive to horizontal branch stars. This makes spectroscopic follow-up of globular clusters in nearby galaxies much more efficient.

**Near-field cosmology:** The ultraviolet excess, driven by the sensitivity of the u-band magnitude to line blocking by the plethora of metal lines, can isolate and obtain metallicity estimates for metal-poor stars. The u-band and narrowbands of KWFI are able to break the degeneracy between surface gravity and metallicity and detect rare extremely metal-poor stars. In addition, deep, wide-field u-band imaging can help confirm faint Milky Way dwarf galaxies for dark matter studies and radio HI follow-up. Deep, wide-field imaging can search for dwarf galaxies in Andromeda and other galaxies to help rectify the ‘missing satellite’ problem.
**Optical design**

KWFI is designed to be a simple workhorse facility instrument for high efficiency operations. It will have high throughput, fast readout, fast filter change, and a design to minimize installation time. Having only 4 optical elements minimizes overall instrument cost. Delta-doped CCDs provide excellent UV sensitivity, and are one option, but a similar and acceptable sensitivity might be achieved with a commercial CCDs made by Semiconductor Technology Associates and backside treated by Imaging Technology Labs that would reduce costs. KWFI will be equipped with 15 µm pixel CCDs, corresponding to 0.178” pixel⁻¹. CCDs remain an attractive technology since cost per unit area is low and on chip binning can be employed to adapt to seeing conditions, but as CMOS technology evolves during the course of the study this option will be kept open.

Figure 2 shows the layout of KWFI corrector lenses in comparison with those of the Subaru Hyper-Suprime Cam and the CFHT Megacam correctors. KWFI will be much less expensive than Subaru Hyper-SuprimeCam. The design is optimized for the Keck u and g spectral windows but will give good image throughput and image quality through the z-band.

The corrector design here covers a field 0.5° square (with diagonal 0.707°), but can be 1.0° diameter. It accepts some vignetting (~10% in the corners of the field) and has the largest element outside diameter of 1000 mm. The simple KWFI design needs only one non-spherical surface and that is a concave prolate ellipsoid, which could be null-tested in reflection. This baseline version has also dispensed with an atmospheric dispersion corrector (ADC), enabling the omission of one lens element, leaving just four, including the one that will be used as the CCD dewar window.

A version with an ADC, which would have superior performance at zenith distances (ZDs) greater than ~30°, is feasible without requiring other than silica lens elements. The design would require a novel mechanism to offset and tilt the ADC elements and would be substantially more expensive.
Above is a 3D side view (left) and back view (right) schematic of KWFI in the secondary carriage (cf. Figure 1.). Lenses are shown in blue, filters in tan, and the dewar window in green. Two filter wheels placed in tandem will enable 11 filters (ugriz and 6 narrowband or visitor filter slots).

Figure 3 shows the spectral transmission of the corrector lens if its 8 surfaces can be optimally coated with solgel over MgF₂. With the simplest broadband coating – just MgF₂ – the transmission over the u window would average ~87%. Figure 4 shows the extent of the vignetting loss, reaching ~10% in the corners of the square field.

Without an ADC, the image quality in the u window is compromised for any ZD greater than ~30°. The diameters enclosing 80% energy at the worst field position with the simulation adopted for the Keck u filter are 0.36”, 0.76”, and 1.09” at ZD 0, 45° and 60°, respectively. In Figure 5, the impact of this is shown across the field with a contour plot of rms image radius.

An obvious strategy to alleviate this effect is to split the u band-pass into two sections, here termed u₁ and u₂. The Keck u pass-band has been represented by equally weighted wavelengths 327+351+370 nm, the u₁ pass-band is represented by 327+335+345 nm, and the u₂ pass-band by 342+354+370 nm. The worst diameters enclosing 80% energy are 0.38”, 0.49”, and 0.63” for u₁ and 0.32”, 0.52”, and 0.72” for u₂, for ZD 0, 45° and 60° in each case. Consideration of Figure 5 indicates that these d₈₀ figures give a somewhat pessimistic indication of performance insofar as the worst values are restricted to a relatively small area of the field near its periphery.
To better judge the effect of the aberrations and atmospheric dispersion in practice, simulations have been made in Zemax combining these effects with the best seeing expected on rare occasions. From special optical tests on Keck I through 1994 and 1995 (Gillingham, P., 1996, SPIE, 2871 pp 2-14), only one of ~100 full aperture images had a FWHM significantly better than 0.4 arcsec (with effective wavelength 650 nm). Seeing diameter is proportional to $\lambda^{-0.2}$ and to (air mass)$^{0.6}$. Assuming the ZD of those observations to have averaged ~30° (with air mass
correction for the air mass and wavelength (to 350 nm) gives seeing diameters equivalent to the measured 0.4 arcsec of 0.45", 0.51", and 0.63" at ZD 0, 45°, and 60°, respectively. Figure 6 shows images convolving these seeing values with the optical aberrations and atmospheric dispersion at the worst field position for the three ZDs with the full u pass-band and with that pass-band divided in two.

It is apparent that, even with unusually good seeing, the optical aberrations degrade the images almost negligibly anywhere in the field at the zenith. With the full u pass-band, the atmospheric dispersion at zenith distance 60° very significantly degrades images in the worst field positions in the best seeing, but maybe tolerably at ZD 45°. With the split u pass-band, image elongation even at ZD 60° is likely acceptable.

**Optical design summary**

1. The KWFI relatively simple corrector lens has just four elements, the last of which serves as the CCD dewar window.
2. All elements are of silica so that there is negligible absorption loss from 300 nm to the infrared limit of CCDs.
3. The total weight of the finished optical elements is only ~175 kg.
4. All surfaces are spherical except one, which is a concave ellipsoid, relatively easy to null test in reflection.
5. The focal surface is a plane.
6. The design has been optimised to strongly favour the u spectral window.
7. Observing at or near the zenith in u, there is negligible loss of resolution anywhere in the 0.707° diameter field, with the best seeing to be expected (0.45 arcsec FWHM).
8. At ZD 45°, the performance in the u pass-band is compromised only a little by not having an ADC.
9. At ZD 60°, the performance in u is significantly degraded without an ADC, but would be tolerable if the standard Keck u band was split in two.
10. In the longer wavelength windows, the zenith performance is inferior to that in u (through the weighting adopted in the optical optimization) but there is little degradation through atmospheric dispersion.
11. With substantial additional cost, an ADC could be included without requiring any glass other than silica.
12. With additional cost, a larger field could be served – the Keck top end does not limit it.