Liger: Next Generation Imager and Spectrograph for Keck Observatory Adaptive Optics

Thematic Areas:
Optical and Infrared Observations from the Ground
Astro2020 APC White Paper

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Abstract

We are designing a next-generation adaptive optics-fed integral field spectrograph (IFS) and imaging camera for the W. M. Keck Observatory. This innovative instrument, known as Liger, will be crucial for exploring a wide range of science cases across cosmic time, such as dark matter substructure, distant galaxies, supermassive black holes, nearby star forming regions, the Galactic Center, and Solar System bodies. Liger is designed to be a facility-class instrument that will enable new science by offering enhanced capabilities such as higher spectral resolving power (R∼8000-10000), access to shorter wavelengths (0.84 - 2.4 μm), and larger fields of view compared to any current and future ground- and space-based IFS systems. The Liger instrument uses the latest near-infrared detectors for an imaging camera that operates simultaneously with an innovative IFS that uses both a slicer and lenslet array for spatial sampling. Liger is being planned for the Keck I telescope to take advantage of the upcoming Keck All-Precision Adaptive optics (KAPA) system that will offer significantly improved adaptive optics (AO) performance. The design of Liger builds on a legacy of work from partner projects to minimize costs and fabrication and construction timescales. We are heavily leveraging our experience and design work on the first-light instrument IRIS for the Thirty Meter Telescope to construct the Liger instrument for the Keck AO system. We are currently completing the critical design phase for this instrument, and anticipate starting construction in 2021, with completion and delivery slated for 2026. As a precursor to later instruments on extremely large telescopes, Liger is a crucial stepping stone both technologically and scientifically in the next decade.

Keywords

Ground-based Instrumentation — Adaptive Optics — Near-Infrared

1. Key Science Goals

A next generation AO-fed instrument is crucial for exploring a wide range of science cases at all distance scales - from solar system objects to the most distant galaxies. Integral field spectrographs coupled with adaptive optics (AO) systems have indeed proven to be a revolutionary tool, but the current Keck AO-fed IFS OSIRIS has several limitations. These include a small IFS field of view set by the Hawaii-2RG detector, a single spectral resolving power of R=4000 (i.e., 80 km/s), wavelength coverage that starts at 1 μm, and throughput issues due to a single-fixed grating. Additionally, the coarsest sampling (0.1"/spaxel) of OSIRIS suffers from spectral blending and sensitivity issues. Spectra in this coarsest scale have a width of 3 pixels but are spaced by only 2 pixels from each other. While all OSIRIS spectra require deconvolution (Lyke et al., 2017), this coarse 0.1" scale is particularly problematic and has artifacts which the data pipeline team has struggled to fully resolve. This has especially limited extragalactic observations at low surface brightness where the coarse scale is preferred. Liger will overcome these limitations, and will be designed as a facility-class instrument to address the full breadth of science topics benefiting from a next-generation IFS and imager. In this section we briefly describe several key science drivers that require Liger's new capabilities.

1.1 Distant Galaxies and Cosmology

AO-fed IFS observations have opened new windows into high redshift galaxy studies, and have established the origin of the disk+spheroid Hubble sequence at z>2 (e.g., Genzel et al. 2014). However while kinematics can be mapped with the strongest emission lines, it is extremely challenging to detect fainter lines such as [NII], [SII], and even Hβ. These features are needed to probe metallicity gradients and shocked feedback-driven outflows, and to distinguish the spatial signatures of stellar feedback vs active galactic nuclei (Wright et al., 2010; Newman et al., 2014). The dramatic sensitivity improvement of Liger's coarse plate scales is critical for distant galaxies, and will allow resolved mapping of the general high redshift population. Liger's broader wavelength coverage will observe multiple lines simultaneously, increasing observing efficiency by a factor of $\sim$2. The larger field of view offers further improvement, for example in observing strong gravitationally lensed systems which offer the best means of mapping kinematics and metallicity (e.g., Jones et al. 2013; Leethochawalit et al. 2016; Figure 1).

A fundamental, and still open, challenge for galaxy evolution is studying how the populations of disk galaxies changes from predominantly clumpy and turbulent systems at redshifts z=1–3 (e.g., Elmegreen & Elmegreen 2006), to being dominated by thin disks in the local Universe (van der Kruit & Freeman, 2011). Indeed, IFS kinematic surveys have led our understanding of the formation of the z=0 Hubble Sequence which has remained a fundamental challenge of extragalactic astronomy for nearly 100 years. These surveys tell us that this transition occurs between redshifts z=0.7-1.5, but very little is known about the dynamical transformation during that epoch due to a lack of sufficient observational capabilities. We require higher spectral resolution at bluer wavelengths than current AO facilities can observe. The best line for measuring kinematics is the Hα emission line, corresponding to wavelengths $\lesssim$1 μm at z=0.7. Thin disks have typical local velocity dispersions of 10-20 km s^{-1}, requiring R=8000 for adequate measurements. Finally, as these thin disks have larger angular momentum and are thus more spatially extended, a wider field of view is necessary for survey efficiency. Liger will uniquely provide the wavelength coverage, resolution and field of view needed to probe this transitional epoch.

Considerable progress can be made in understanding dark matter and dark energy by studying strong gravitational lens systems at AO's diffraction-limited resolution (e.g., Vegetti et al. 2010). Current IFS+AO studies have already shown the potential of using gravitationally lensed systems to detect satellites of total mass $\sim 10^8$ $M_\odot$ irrespective of lensed galaxy stellar content (Nierenberg et al., 2017). This is one of the most promising methods for resolving the long-standing dark matter substructure problem (i.e., the "missing satellites" problem). Likewise, gravitational time delays between multiple images of lensed quasars have emerged as a powerful probe of dark energy. A key requirement is to have high spectral resolution (R$\sim$8000) measurements of the lens galaxies at sufficient spatial resolution to obtain resolved stellar kinematics and hence the mass determinations (Shajib et al., 2018). Both of these gravitationally lensed cases will require sufficient IFS field of view (Figure 1) and are well-suited for a higher performance IFS-AO suite delivered by Liger.

1.2 Nearby Galaxies

The astrometric precision of Liger will make it a machine to measure precise proper motions of individual stars. It will exceed the performance of Gaia for faint stars (V $>$ 20) and crowded fields (e.g., the cores of globular clusters). For example, multi-epoch imaging of the core of a globular cluster, like Terzan 5, will yield proper motions precise enough to measure a velocity dispersion from tangential velocities alone. A key science case is to measure kinematic signatures of intermediate mass black holes (IMBHs)

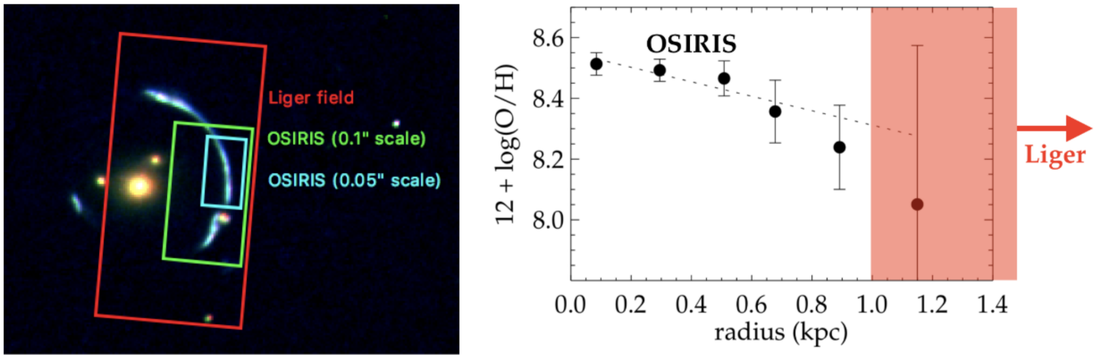

Figure 1. IFS observations of a z=2.01 lensed galaxy (SDSS J1206+5142, magnified ∼28x by a galaxy group at z=0.42). Left: Liger's field of view will allow the entire arc and central lens to be observed in one pointing, whereas OSIRIS requires multiple positions even at the largest scale. Right: Metallicity gradient (O/H) of the lensed galaxy measured from OSIRIS data in the central R $<$ 1 kpc, where the requisite faint emission lines are detected (Jones et al., 2013). Liger's slicer field of view and considerably higher sensitivity will map low surface brightness emission lines at larger radii, improving gradient measurements and enabling diagnostics of shocked outflows and active galactic nuclei. Observations of similar lensed quasar systems will enable sensitive probes of dark matter substructure and dark energy, utilizing Liger's field of view and higher spectral resolution.

in globular clusters and in nuclei of low-mass galaxies. Detections of IMBHs, and limits on their occupation fraction in globular clusters, are of vital importance in understanding the origin of supermassive black holes in galactic nuclei. This requires the high astrometric precision of Liger imaging coupled with IFS to measure 3D velocity dispersion profiles. Liger's R∼10,000 spectral resolution mode is essential for kinematic tests in this regime, where the velocity dispersion is only ∼15 km s^{-1}. High Strehl observations in K-band will provide radial velocities via the CO bandheads, while short wavelength coverage will uniquely provide AO spectroscopy of the Ca triplet at 0.85 μm, envisioned as a key kinematic probe for next-generation instruments and ELTs (e.g., Greene et al. 2019).

The wavelength coverage of Liger will allow for the study of near-infrared emission lines arising from star formation which give constraints on the ages and excitation mechanisms of star-forming regions (e.g., Paβ, Brγ, [Fe II]; Dale et al. 2004). The high spectral resolution of Liger will allow the nearby [FeII] and Paβ lines to be deblended, with the ratio of these lines being a useful probe of the excitation mechanism of star-forming and nuclear regions (e.g., Larkin et al. 1998). The widest field of view IFS mode will allow for nearby HII regions and complexes to be mapped in a single pointing, while the high spatial and spectral resolution will also allow for the compact extent and kinematics of the smallest star-forming regions to be resolved.

1.3 Galactic Center

Higher spectral resolution and larger fields of view will be critical for a range of Galactic science cases (Do et al., 2019). For the Galactic Center, Liger's higher spectral resolution and higher sensitivity are important for precision stellar radial velocities and orbital solutions, and to study the elemental abundances of the elusive stellar population (e.g., Paumard et al. 2006; Lu et al. 2013). Higher spectral resolution will also reduce systematic errors in spectral classification of stars, for example by deblending Brγ emission from the nearby He line. Liger's wider field IFS will additionally allow a dramatic increase in the number of stars with high-quality spectra in the instantaneous field of view, including several with short-period orbits (see Figure 2). The larger field of view of the imager will also be critical for achieving high astrometric accuracy with additional reference sources (Do et al., 2013).

1.4 Star Formation

The wide field of view of Liger coupled with diffraction-limited performance in the near-infrared offers a perfect tool for studying young, embedded star forming regions. Understanding the central parts of star forming regions at high resolution is critical for modeling the mass of stars and the initial mass function (e.g, Hosek et al. 2019). Liger has the capability to gather the spectra of 10s-100s of stars in a single pointing, offering both spectral type and kinematic information that is essential to gathering a full census of the stellar population. The internal velocity dispersions of nearby young clusters are small (e.g., Tobin et al. 2009), and thus increased spectral resolution, with the corresponding improvement in radial velocity precision, will allow for the measurement of the individual motions of stars in the cluster. Such measurements can offer a probe of velocity anisotropies as a function of stellar properties, which in turn can be compared to models of cluster formation. In addition, the higher spectral resolution mode and shorter wavelength capabilities will offer a new window for probing individual young stars, including studying the winds from massive stars (e.g., Oksala et al. 2013), spectral typing and orbital monitoring of binary systems (e.g., Schaefer et al. 2018), and studying disks and outflows in young stars and protostars (e.g., Perrin & Graham 2007).

1.5 Extrasolar Planets

IFS studies of directly imaged planets have provided arguably the best spectra of any exoplanets to-date (e.g., Konopacky et al. 2013; Barman et al. 2015; Hoeijmakers et al. 2018), with Liger's predecessor OSIRIS taking the first spectrum of a directly imaged exoplanet (Bowler et al., 2010; Barman et al., 2011). The spectral resolution of current IFSs is vastly greater than the instrumentation used to perform transit spectroscopy from space, enabling the identification of individual atomic and molecular features in young Jovian atmospheres. Liger has the potential to transform our ability to characterize extrasolar gas giant worlds by offering R$\sim$8,000-10,000 spectral resolution coupled with shorter wavelength coverage. Current studies have focused primarily on the near-infrared K-band, where molecules such as carbon monoxide, methane, and water dominate. Higher spectral resolution will allow for a significant improvement in the derivation of the abundances of carbon and oxygen, which are key probes of the planet formation process (e.g., Öberg et al. 2011). Higher spectral resolution will also offer the opportunity to measure radial velocities of planetary companions, a difficult task with current instrumentation. Radial velocities will provide much stronger constraints on the orbital properties of these planets, which can inform their early dynamical history (e.g., Chatterjee et al. 2008).

1.6 Solar System

IFSs on spacecraft and ground-based telescopes have been critical to planetary science studies of the giant planets, satellites, and small bodies such as Kuiper Belt Objects. Placing our solar system into the context of diverse planetary systems around other stars will help us address whether the building blocks and evolutionary path that lead to habitability in our Solar System are unique.

A current high-priority NASA objective is to explore the ice giants Uranus and Neptune (Hofstadter et al., 2017). Previous studies have used resolved spectroscopy (often limited to R$<$1000) to understand the cloud structure in these atmospheres, thanks to the variable absorption of CH_4 and H_2 in the near infrared (e.g., de Kleer et al. 2015; Luszcz-Cook et al. 2016). Recent Gem-

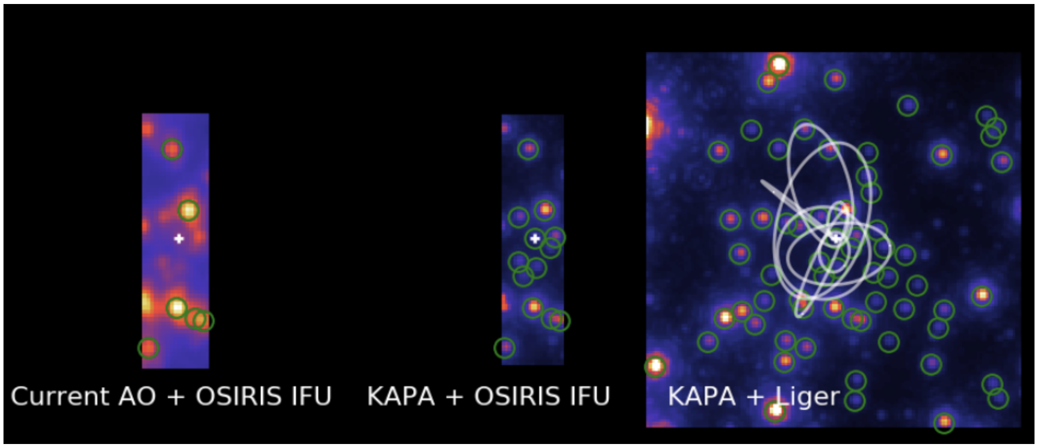

Figure 2. Simulated Galactic Center observations using Liger (right) compared to OSIRIS (left). Liger's increased field of view and sensitivity yields a dramatic increase in the number of stars with precise radial velocity measurements (indicated with green circles), including several with short-period orbits (white ellipses).

ini NIFS observations of Uranus and Neptune with improved R∼5000 *H*-band spectra have demonstrated weak detections of H_2S (Irwin et al., 2018, 2019), which could support suggestions of nitrogen/sulfur ratios <1 from prior microwave studies (de Pater et al., 1991). Liger will probe the dominance of H_2S over NH_3 in the observable atmosphere which has profound implications for the accuracy of our models of cloud chemistry (Lewis, 1969; Weidenschilling & Lewis, 1973), and for the microwave opacity that would be encountered by a future atmospheric entry probe to either of these planets.

Tracing how water arrived at the terrestrial planets is a key priority question of the recent Astrobiology Strategy Report (NAS, 2019). Small primitive bodies are used as tracers of the history of water in the early solar system. There is now direct evidence that the outer asteroid belt is wet. Both water vapor and ice have been detected on a number of the largest bodies in the outer asteroid belt. Recently, smaller bodies in the outer belt, called Main Belt Comets (MBCs), have been found to exhibit comet-like tails. The MBC activity is due to outgassing of volatiles from ices preserved in their interiors. Unlike the larger asteroids in the outer main belt, MBCs are small enough to have escaped hydrothermal processing and are thus comprised of pristine ices leftover from the early solar system. Liger will simultaneously cover two water ice features, reducing concerns over variation of surface features due to rotation of the small body. For periodic and dynamically new comets, Liger's higher spectral resolution and higher sensitivity will be important for determining changes in the production rates of water and hydrogen cyanide across the coma.

2. Technical Overview

Liger is being designed for the Keck I telescope to operate behind the current laser guide star system, as well as to take advantage of the upcoming Keck All Precision Adaptive optics (KAPA) system. KAPA will include a new LGS facility for atmospheric tomography, and provide enhanced near-infrared tip-tilt sensing and point spread function (PSF) reconstruction. KAPA will increase the image quality (i.e. Strehl ratio) by a factor of 1.7 for the extra-galactic and exoplanet imaging projects that were previously observable (i.e. Strehl $>$ 0.2, sky coverage ¡ 30%). KAPA also opens up access to an additional 60% of the sky. The resulting KAPA system will have dramatically higher sky coverage with higher Strehl ratios allowing it to operate at shorter wavelengths. Without Liger, many of these improvements will not be fully exploited. Like previous AO instruments, the KAPA enclosure provides a clean working environment for the instrument and access for servicing. Liger will be mounted on a rail cart that allows it to move out of the enclosure onto the deck when not in use, and to move back and effectively dock with KAPA.

2.1 Design Heritage - TMT IRIS

Liger is an outgrowth of the long term project to design and build an integral field spectrograph called IRIS (Infrared Imaging Spectrograph) for the Thirty Meter Telescope (TMT). As a diffraction-limited instrument, many of the optical systems designed for TMT can be immediately brought to Keck with platescales that scale directly with telescope size. The IRIS designs, including precision cryogenic mechanisms like the grating turret, also provide for greater efficiency at all wavelengths and the ability to significantly increase the wavelength range into the optical and are an excellent match to the improved capabilities of the KAPA system.

IRIS is currently in the second year of a three year final design phase. At the end of 2020, the team expects to have fabrication ready designs of all components including electronics and software. It will also have vendor quotes on all items and a team structure needed for the instrument's completion. TMT management is aware of the Liger project and very supportive. They see Liger as a method of reducing technical risk and engaging vendors.

2.2 Subsystem Overview

Liger covers the wavelength range from 0.84-2.4 μm and combines a diffraction limited integral field spectrograph and wide-field imager. Both systems use the latest infrared detectors and have four times as many pixels as the existing OSIRIS instrument. This can cover greater fields of view, but also offers better sampling and more spectral channels. The camera is custom for Liger, while the IFS channels are identical to the IRIS slicer and lenslet systems. The camera and spectrograph view light first passes through the imager optics including its filter set and cold pupil stop. Two small pickoff mirrors close to the imaging detector direct the light into the lenslet and slicer systems. This reduces the number of complex mechanisms and optical elements and also provides some significant performance improvements. It also allows the Keck adaptive optics system to sharpen the image all the way to the imager's detector while also improving the IFS optical performance. The large pupil within the imager also allows for better masking of the thermal background than would occur within the reimaging optics for the IFS. The overall optical path of Liger is shown in Figure 3.

Liger can be used with the Keck AO system in either natural guide star mode or laser guide star mode. The Liger imager and IFS will operate simultaneously on-sky and use the same filter wheel and rotating Lyot stop. The lenslet spectrograph offers 14 and 31 mas plate scales and the slicer spectrograph 75 and 150 mas plate scale. The selection of the filter and grating determines the field of the view of the IFS. The full capabilities and user options for Liger are defined in Table 1.

2.3 Imager

The imager is optimized for high throughput and low wavefront error. The output focal ratio of the adaptive optics system (F/15) and is converted to a F/37.1 beam that provides an optimal plate scale of 10 milliarcsec per pixel and a 20.5”x20.5” field of view with the Hawaii-2RG detector. A simple, but highly polished, pair of off-axis parabolas (OAPs) provide an achromatic system with no intrinsic ghosts, few optical surfaces and a high quality collimated space in between. Our goal was to produce a moderately sized (24.5mm) intermediate pupil image both for masking thermal emission and for high

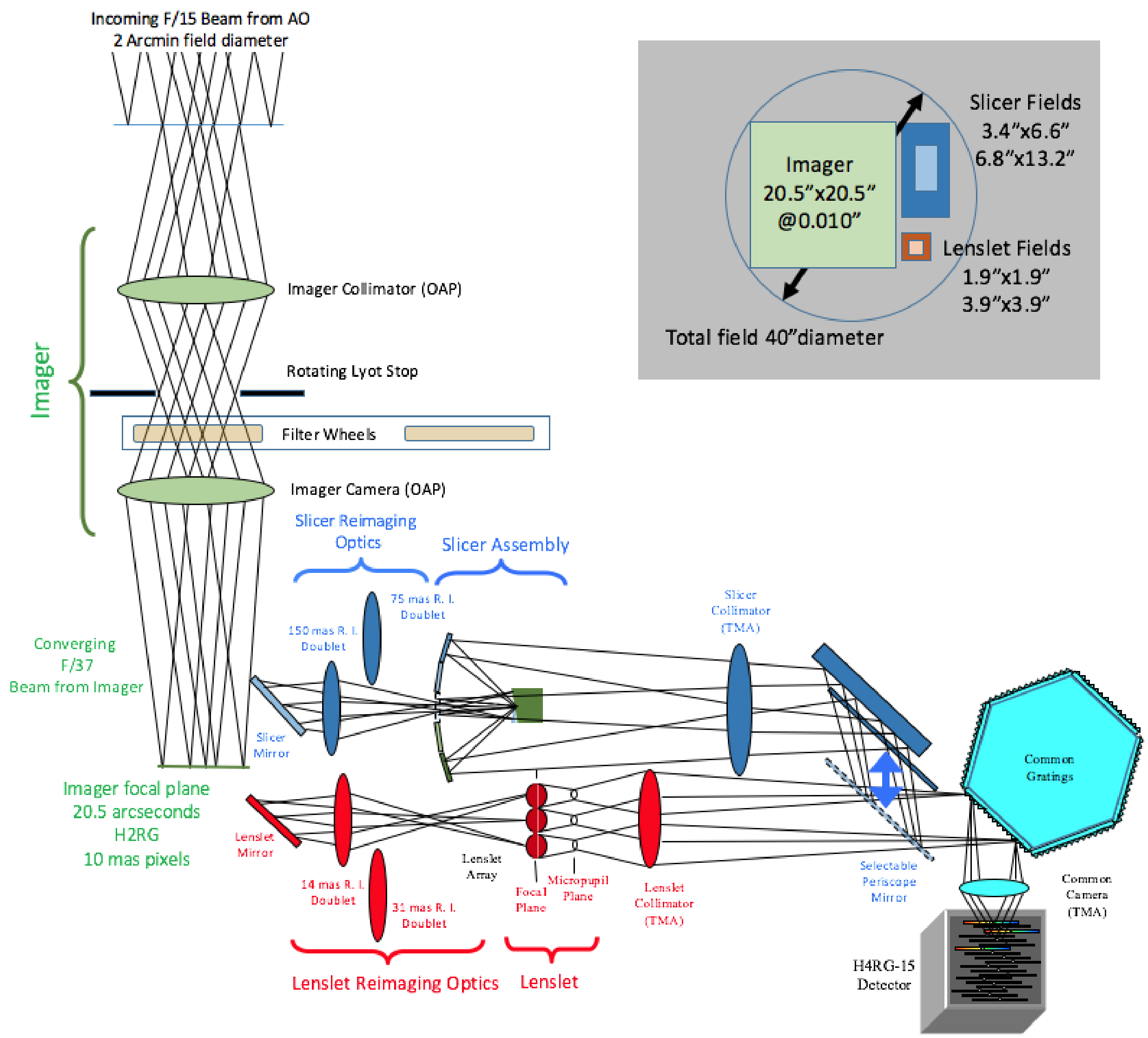

Figure 3. Opto-mechanical layout of the Liger imaging camera (green) and the lenslet re-imaging optics (red) and the slicer re-imaging optics (blue). The Keck AO f/15 beam is fed into Liger at the top left. The filter wheel and rotating lyot stop feeds both the imager and integral field spectrograph. There are two pick-off mirrors that can select between the slicer and lenslet IFS modes. The slicer and lenslet IFS share all complex optics like the gratings, common TMA camera, and detector (bottom right). The nominal field of view of the Liger optical system is in the top right with imaging camera (green), two spatial scales slicer IFS (blue), two spatial scales lenslet (red).

performance filters. This small pupil size enables us to produce a filter wheel assembly with a large number of filters. We are designing a multi-wheeled filter mechanism based both on existing OSIRIS wheels and IRIS designs. A rotating pupil mask will provide thermal baffling for both the imager and IFS system.

2.4 Integral Field Spectrograph

The IRIS project spent several years exploring and comparing different strategies for integral field spectroscopy. The resulting design combines a lenslet array based spectrograph for the two finest platescales and a mirror slicer for the two coarsest scales. It was also found that this ar-

Capability mode	Spatial sampling (mas)	Field of view (arcseconds)	Spectral resolution(R)	λ_{min} - λ_{max} (μm)	Bandpass
Imager Hawaii-2RG	10 mas	20.5 x 20.5	Set by filter	0.84 - 2.4	BB and NB
Lenslet IFS					
128x128 spaxels	14 mas	1.9 x 1.9	4000	0.84 - 2.4	5%
128x128 spaxels	31 mas	3.9 x 3.9	4000	0.84 - 2.4	5%
16x128 spaxels	14 mas	0.2 x 1.9	4000, 8000, 10000	0.84 - 2.4	5%, 20%
16x128 spaxels	31 mas	0.5 x 3.9	4000, 8000, 10000	0.84 - 2.4	5%, 20%
Slicer IFS					
88x45 spaxels	75 mas	6.6 x 3.4	4000	0.84 - 2.4	5%, 20%
88x45 spaxels	150 mas	13.2 x 6.8	4000	0.84 - 2.4	5%, 20%
44x45 spaxels	75 mas	3.3 x 3.4	4000, 8000, 10000	0.84 - 2.4	5%, 20%, 40%
44x45 spaxels	150 mas	6.6 x 6.8	4000, 8000, 10000	0.84 - 2.4	5%, 20%, 40%

Table 1. Liger imager and integral field spectrograph observational modes.

rangement greatly simplified both types of spectrographs and allowed all platescales to share a common grating turret, three mirror anastigmat (TMA) camera and detector. The grating turret is the most complex mechanism in the entire instrument, and the camera TMA is the most complex optical subsystem. To produce the fast (F/4) optical camera for the large format Hawaii-4RG detector, co-PI Renate Kupke (UCSC) produced a TMA camera system using 8th order aspheric mirrors and having a 100 mm pupil for the gratings (see Figure 4). We have now partnered with Aperture Optical Systems (AOS) to procure a prototype mirror and demonstrate our ability to assemble such mirrors at the required 50-75 micron tolerance in a cryogenic environment. Our procedure builds on the alignment of the UCLA IR lab procedures from Gemini Planet Imager IFS (Larkin et al., 2014) and the MOSFIRE (McLean et al., 2012).

To preserve the excellent image quality of KAPA and the imaging camera, the Liger IFS uses simple reimaging optics to transfer the focal plane from the camera to either the lenslet array or slicer module. With few optical surfaces and image sharpening by the AO system all the way to the camera focal plane, we estimate non-common path wavefront errors at 40 nm in the IFS, allowing for extremely sharp imaging within the spectrograph. This, along with shared complex elements, is one of the most important reasons for the sequential design of the image being a set of foreoptics to the IFS.

The most complicated mechanical components of Liger have already been designed and analyzed for IRIS, and some of these components are currently being prototyped at UCLA and Caltech. The mirrors in Liger are made of zeroduer and will be mounted through epoxy pads on their rear surfaces to individual invar flexures which in turn are mounted to aluminum backing plates and mounts. The thermal mismatches at each optic are handled at the interface between the invar and aluminum and separated from the glass surfaces. Each large subassembly like the TMAs are built into an aluminum housing with predictable thermal contraction properties. The large mirror mounts (Figure 4) are based on prototype results and operational experience from heritage programs such as MOSFIRE.

2.5 Dewar & Cryogenics

The dewar or cryostat is a large rectangular aluminum box mounted on three kinematic points on the deck of the AO enclosure. A set of jacks are used to raise the dewar in place so it is supported on the cart system for removal from the AO enclosure on the Keck Nasmyth rails. The dewar itself consists of a lower large flat plate that in turn supports the internal optical bench

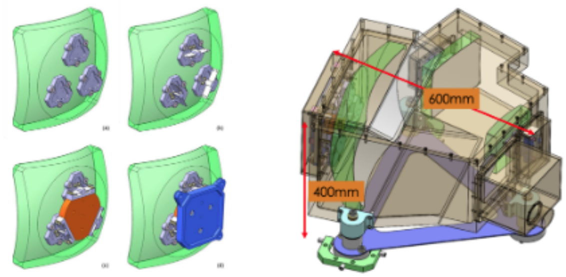

Figure 4. CAD rendering of the large mirror mounts for the Liger collimator and camera optics. The mirrors will be made of low-expansion glass mounted on titanium and aluminum mounts in aluminum boxes (right).

and cold assembly on a set of G-10 A-frames for thermal isolation. The sides and top of the dewar are a single welded structure that can be lifted off the base to give access to the cryogenic subsystems. Figure 5 is a rendering of the proposed dewar volume (orange) containing all of the Liger optical, mechanical and some electrical systems. The majority of its electronics will permanently reside in the AO electronics vault which has its heat removed from the dome environment. A small housekeeping electronics rack will ride on the cart with Liger in order to monitor internal temperatures and dewar pressure. Keck Observatory has a system of helium compressors and vacuum jacketed lines that provide multiple locations on the telescope ports for closed cycle refrigerators (CCRs). Past instruments like NIRC2, NIRSPEC, OSIRIS and MOSFIRE have used CTI 1020 and 1050 cold heads depending on their thermal requirements including detector operating temperature (usual in either the 30 or 77 Kelvin range). The current plan is to use two identical refrigerators from the same line in Liger.

3. Organization & Partnerships

3.1 Management & Status

Liger is currently funded through its preliminary design phase, with an upcoming external

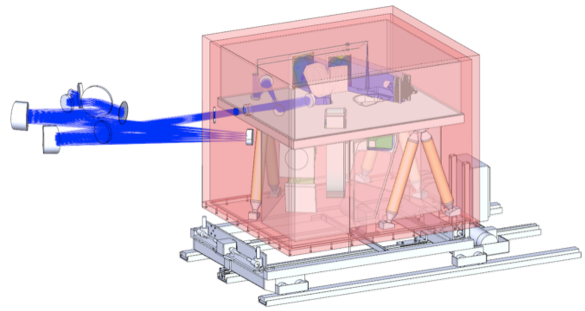

Figure 5. A rendering of a rectangular Liger cryostat. The white optics with blue beams on the left are the locations and beam sizes from the Keck Adaptive Optics system. The lower white structure is the existing cart on a solid model of the Keck rail system located at the output port location of Keck AO. Inside the brown rectangular dewar are all optics with their housings removed and on the top renderings of the OAP imaging system.

review in September 2020. Liger is a modular instrument with varying subsystems and therefore lends itself well to being fabricated at different partner institutions. We have a work breakdown structure of Liger sub-systems with institutional leads for each component. The project will operate with multiple parallel tasks to be executed at the primary institutions - UC San Diego, UC Los Angeles, UC Santa Cruz, UC Davis, Caltech, and Keck Observatory. All performing institutions involved in the fabrication and delivery of Liger adhere to management and documentation procedures and protocols established by Keck Observatory.

3.2 U.S. Community Involvement

Liger has far reaching scientific and community impact to national and international astronomers. Publication metrics indicate that Keck is one of the most scientifically productive telescopes in the world. Keck outpaces all space- and ground-based optical telescopes with the highest average number of citations per paper. Keck has produced 66% of all laser guide star AO publi-

	Major phases and milestones	Expected Timeline	# months
1	Final design & drawings	Jan 2021 - Sep 2021	9
2	Procurement of major optical and detector components	June 2021 - Feb 2023	21
3	Subsystem fabrication (imager, spectrograph: slicer, lenslet, common)	Oct 2021 - Feb 2024	33
4	Delivery, assembly, verification of all subsystems (imager, IFS, dewar)	Mar 2024 - Jan 2025	11
5	Delivery and integration of Liger at W.M. Keck Observatory	Feb 2025 - May 2025	4
6	Commissioning of Liger W.M. Keck Observatory	June 2025 - Dec 2025	7

Table 2. Liger milestones over 5 years from Final Design Phase through Commissioning.

cations worldwide, highlighting the demand for premier AO instruments such as Liger. While a private observatory, Keck maintains a large national/international user community, with 60% of Keck papers in 2015-2017 led by observers outside partner institutions.

The Liger science team was recently developed in 2019 and we are continuing to expand with broader U.S. community and participation. Liger will be delivered with an advanced data reduction system that is based on the 'stpipe' architecture used for the JWST pipeline. The data pipeline also dynamically interfaces to a Calibration References Data System (CDRS), to retrieve the best calibration datasets for an observation. These new tools are planned to be integrated to Keck Observatory Archive (KOA) to allow access to advanced data products for the public user.

4. Schedule & Cost Estimates

The Liger project is currently in the preliminary design phase and is funded by the Heising-Simons Foundation (HSF) until December 31, 2020. During the HSF proposed period our team will aim to produce the following: (1) technical and science trade-studies of the top-level requirements of the Liger instrument; (2) Liger end-to-end science simulations to explore feasibility and sensitivities; (3) overall system engineering design of the Liger instrument; (4) opto-mechanical design of near-infrared camera, filter wheel, and pupil mechanisms; (5) mechanical engineering that adapts the IRIS opto-mechanical structures for the Liger IFS and dewar; (6) basic software design to co-align with Keck requirements; and (7) prototyping and laboratory characterization of Liger gratings and IFS sampling modes. A Preliminary Design Review will be held in Fall 2020. The Liger program following the preliminary design is split between: Final Design Phase, Fabrication, Assembly, Integration, & verification, and commissioning. Table 2 lists major milestones and goals over the course of the five year program starting in the Final Design Phase in January 2021.

The Liger program has been fully-costed with all major equipment vendor quotes including labor estimates for each subsystem. Liger conducted an external cost and programatic review in June 2019. The Liger WBS is divided into major instrument components and assigned to primary and secondary institutions. The assignment of each component and/or subcomponent is managed by that lead institution. These assignments are used to facilitate the schedule, costing of the instrument, and define each institutions statement of work and reporting. The total number of full-time equivalent (FTE) for the program end-to-end starting from Final Design Phase to commissioning is 51.9 FTE. Keck Observatory now mandates that every instrument program includes an overall 30% contingency in their budget. For each subsystem our team has assigned a technical, labor, and vendor risks that is used in the budget. The total cost of the full-scoped instrument is $17.6M, this includes labor ($4.8M), equipment ($8.3), expenses and supplies ($0.5M), and 30% contingency ($4.0M).

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