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IGRINS at the Discovery Channel Telescope & Gemini South

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ABSTRACT

The Immersion GRating INfrared Spectrometer (IGRINS) was designed for high-throughput with the expectation of being a visitor instrument at progressively larger observing facilities. IGRINS achieves R$\sim$45000 and $> 20{,}000$ resolution elements spanning the H and K bands (1.45-2.5μm) by employing a silicon immersion grating as the primary disperser and volume-phase holographic gratings as cross-dispersers. After commissioning on the 2.7 meter Harlan J. Smith Telescope at McDonald Observatory, the instrument had more than 350 scheduled nights in the first two years. With a fixed format echellogram and no cryogenic mechanisms, spectra produced by IGRINS at different facilities have nearly identical formats. The first host facility for IGRINS was Lowell Observatory's 4.3-meter Discovery Channel Telescope (DCT). For the DCT a three-element fore-optic assembly was designed to be mounted in front of the cryostat window and convert the f/6.1 telescope beam to the f/8.8 beam required by the default IGRINS input optics. The larger collecting area and more reliable pointing and tracking of the DCT improved the faint limit of IGRINS, relative to the McDonald 2.7-meter, by $\sim$1 magnitude. The Gemini South 8.1-meter telescope was the second facility for IGRINS to visit. The focal ratio for Gemini is f/16, which required a swap of the four-element input optics assembly inside the IGRINS cryostat. At Gemini, observers have access to many southern-sky targets and an additional gain of $\sim$1.5 magnitudes compared to IGRINS at the DCT. Additional adjustments to IGRINS include instrument mounts for each facility, a glycol cooled electronics rack, and software modifications. Here we present instrument modifications, report on the success and challenges of being a visitor instrument, and highlight the science output of the instrument after four years and 699 nights on sky. The successful design and adaptation of IGRINS for various facilities make it a reliable forerunner for GMTNIRS, which we now anticipate commissioning on one of the 6.5 meter Magellan telescopes prior to the completion of the Giant Magellan Telescope.

Keywords: infrared spectrograph, cryogenic, immersion grating, sensitivity, visiting instrumentation, McDonald Observatory, Discovery Channel Telescope, Lowell Observatory, Gemini Observatory, Giant Magellan Telescope

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1. INTRODUCTION

The Immersion GRating INfrared Spectrometer (IGRINS),[1–3] with its panoramic view of the near-infrared H and K bands, has broadened our perspective of young stellar objects (YSOs), the interstellar medium (ISM),[4] and stellar abundances. A single observation with IGRINS simultaneously probes both the stellar photosphere and disk of YSOs.[5–9] Observations of star forming regions with IGRINS provides position and velocity information in addition to temperature diagnostics.[10–14] With R$\sim$45,000, IGRINS resolves the emission of exotic elements within planetary nebulae[15] and the absorption spectra of alpha process elements in the photospheres of evolved giant stars.[16–18] The combination of these science cases span from the origin of star and planet formation,[19] across the evolutionary history of the Milky Way,[20] to the current census of star and planet properties.[21–29] Since early 2015 there have been 33 peer-reviewed science papers, and many more are in preparation.

The characteristics which allow IGRINS to produce unique perspectives on well-studied topics in astronomy are its sensitivity and broad spectral grasp. The limiting magnitude of IGRINS (SNR$\sim$100 in 1 hour of exposure time) on the 2.7 meter Harlan J. Smith Telescope (HJST) at McDonald Observatory is the same (to within 0.5 magnitudes, depending on seeing) as NIRSPEC on Keck,[30] iSHELL on the IRTF,[31] and CRIRES on the VLT.[32][33] When IGRINS is on Lowell Observatory's 4.3-meter Discovery Channel Telescope (DCT) and the 8.1-meter Gemini South telescope, it is the most sensitive, high-resolution near-infrared spectrograph anywhere in the world. The sensitivity and spectral grasp of IGRINS is permitted by the development of silicon immersion gratings at the University of Texas at Austin.[34–38] When infrared light longward of 1μm is immersed inside silicon the dispersion angle is scaled as the index of refraction (n$\approx$3.43 for silicon at 130 K[39]). This increase in dispersion provides for a compact instrument design while still obtaining broad wavelength coverage at high-resolution. IGRINS was designed with a single instrument setting and the expectation that it would be a visitor instrument. Spectra obtained with IGRINS are wavelength invariant wherever they are obtained. In order to keep the echellogram fixed in resolution and position, all adjustments to IGRINS' optics are made in front of the spectrograph slit, which sees the same f/10 beam at all facilities. As a result, the slit mask maintains the same physical dimensions but the projected slit size on-sky scales with the telescope diameter. The slit is $1'' \times 15''$ on the HJST, $0\farcs63 \times 9\farcs3$ on the DCT, and $0\farcs34 \times 5''$ on Gemini South.

When comparing IGRINS at different facilities to other high-resolution, near-infrared spectrographs we need to consider typical conditions for each site. When the target full width at half maximum (FWHM) of the point spread function (PSF) is greater than the slit width, slit loss occurs. The IGRINS slit was chosen to be the same size as the typical K-band FWHM of a point source on the HJST at McDonald Observatory, which is $\sim1\farcs0$. Moving IGRINS to the 4.3-meter DCT reduced the projected slit width to $0\farcs63$, while the typical FWHM measured in 2015 at the DCT was $1\farcs25$[40] at visible-light wavelengths. During the first visit to the DCT, in 2016, IGRINS K-band FWHM's were $0\farcs8$-$1\farcs0$ on clear nights. Slit loss in typical conditions modifies the faint limit for IGRINS at the DCT and it is fairly similar to IGRINS on the HJST. However, this faint limit is much improved when the FWHM is $0\farcs6$ or less, in which case we realize the $\sim$1 magnitude improvement expected from the increase in telescope diameter. The IGRINS slit width at Gemini South is $0\farcs34$, and the typical K-band FWHM is $\sim0\farcs6$. Figure 1 shows the all-sky coverage of IGRINS at McDonald Observatory, the DCT, and Gemini South for their limiting magnitudes with typical conditions. IGRINS at McDonald Observatory and on the DCT can observe a similar number of sources, while the more typical $\sim$1 magnitude improvement provided by Gemini's larger diameter, and its southern hemisphere location increase the number of sources to $\sim$29 million. When the FWHM at Gemini is smaller than $0\farcs4$ the faint limit is increased by an additional 0.5 magnitudes. In Figure 2 we compare the total number of 2MASS point sources[41, 42] observable by similar resolution spectrographs as a function of their location and limiting magnitudes. All assumptions for these comparisons are listed in Table 1. Figure 2 also shows the single exposure spectral grasp of each instrument when normalized to the same $\sim$1 μm range of IGRINS.

To use IGRINS at multiple facilities we considered four primary interfaces: 1) optical, 2) mechanical, 3) utilities, and 4) software. At the DCT this required fore-optics in front of the cryostat window and at Gemini South the input optics inside the cryostat had to be exchanged. Mechanical interfaces were related to the instrument and electronics mounts and lifting provisions, as well as ensuring that mechanical interference was avoided. Utilities included power, coolant, and network communications between IGRINS and the facility.

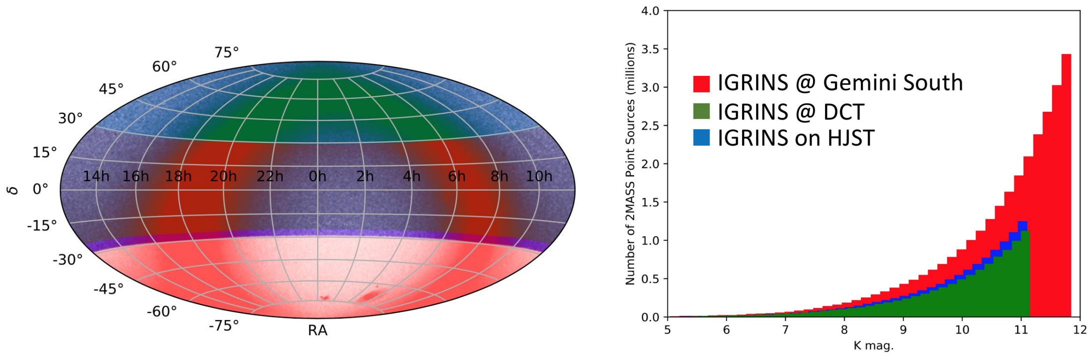

Figure 1 Left: Observable 2MASS point-sources[41,42] when IGRINS is at McDonald Observatory (blue), the DCT (green) and Gemini South (red). These sources are selected to be observable with SNR>100 in 1 hour at <2 airmasses in typical conditions (Table 1). The purple region in the center denotes the overlap observability between all three sites. Right: A histogram of the number of targets plotted on the left. IGRINS at the DCT is more sensitive than on the HJST, but higher latitude and increased slit-loss keeps the number of sources that can be observed at the DCT about the same. Approximately three times more targets are observable at Gemini South than at the other two facilities.

Finally, software adjustments supported communication with the telescope control software, changes for the plate-scale of the slit-viewing camera, and the nuances of observer operations.

2. IGRINS AT LOWELL OBSERVATORY'S DISCOVERY CHANNEL TELESCOPE

The DCT is a 4.3-meter telescope located in Happy Jack, Arizona. The telescope was designed to accommodate up to five instruments at the f/6.1 Ritchey−Chrétien focus. The DCT was fully commissioned at the end of 2014[40,52] and in late-2015 planning began for IGRINS to visit the DCT for periods of ∼6 months in each of the following three years. Given the summer maintenance schedule for IGRINS, it was decided that IGRINS would first visit the DCT from 2016 September to 2017 February, just six months after the formal agreement was signed. All modifications listed in Section 2.1 were completed in these six months. In 2016 August a two day readiness review was held at the University of Texas (UT) at Austin and included two independent reviewers (Prof. John Lacy and Dr. Phillip MacQueen) in addition to project members from Lowell Observatory, the Korea Astronomy and Space Science Institute (KASI) and UT. Commissioning at the DCT was on 2016 September 7 & 8, with first light occurring on the second night. The first-light spectrum was an ABBA slit-nod sequence of 240-second exposures (960s total) of the radial velocity variable binary Wolf 1130AB. This spectrum was compared to the previous observations of the binary with IGRINS on the HJST[20] and the expected sensitivities were confirmed to be ∼1 magnitude when the FWHM was comparable to the slit width.

Between the first and second visit to the DCT, IGRINS went to McDonald Observatory and 18 months elapsed between maintenance periods instead of the customary 12 months.[*] The second visit to the DCT started in 2017 September and ended in 2018 January. IGRINS visited Gemini South between the second and third visit to the DCT, and this is discussed in Section 3. The third IGRINS visit to DCT is planned from 2018 September to 2019 April.

2.1 Modifications to IGRINS for the DCT

IGRINS' default input optics were designed for use on the HJST, and they convert the f/8.8 beam from the telescope to the f/10 beam expected at the slit mask. As shown in Figure 3, the input-optics assembly is located

[*]In the summer months we used FedEx Custom Critical to temperature control the instrument at 18.5 C while in transit to the DCT. This was to avoid damaging the H2RG detectors with excessive heat. All other trips between McDonald, the DCT, and UT Austin were handled by the IGRINS Team.

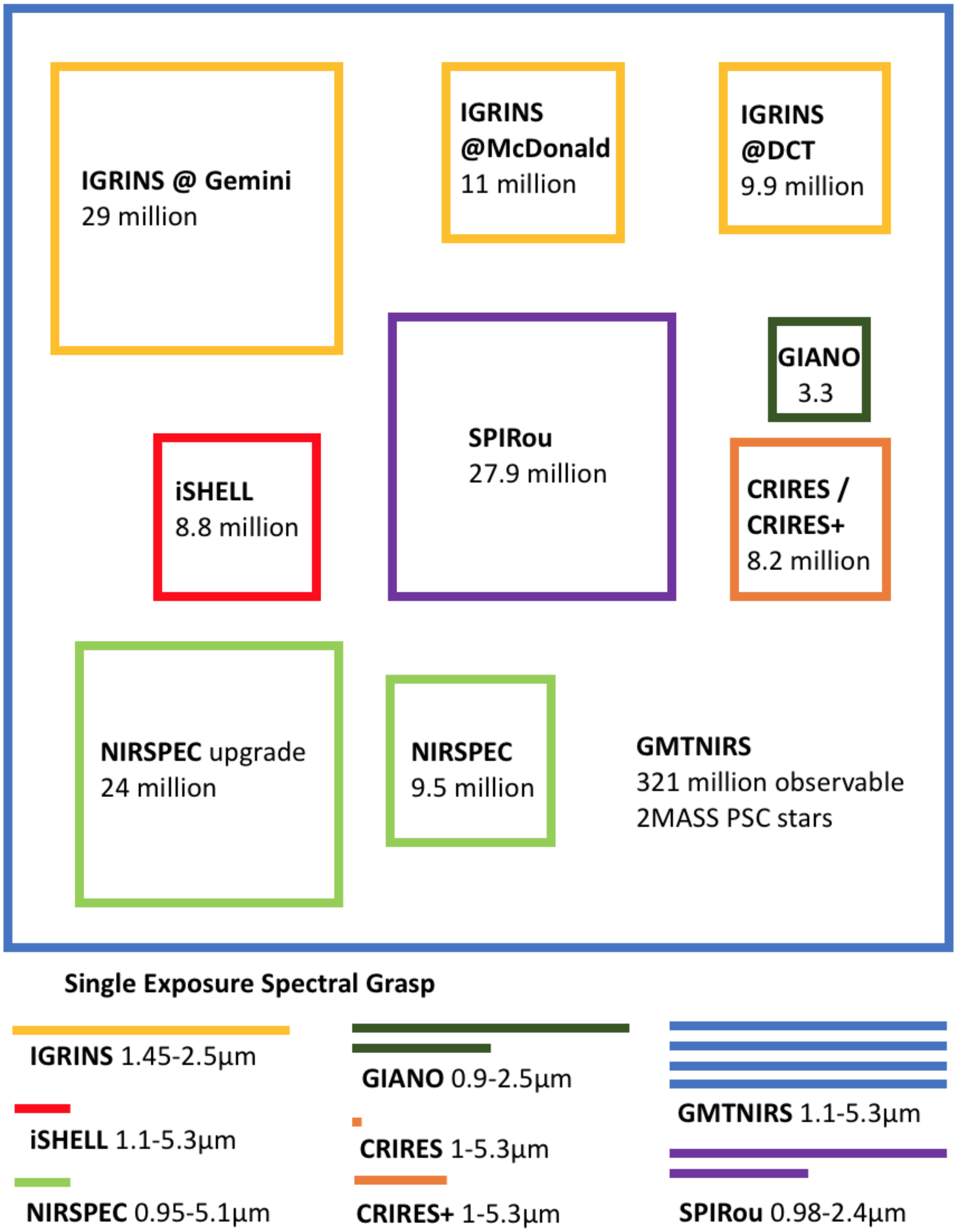

Figure 2 Top: The number of 2MASS point-sources observable with each high-resolution, near-infrared spectrograph (assumptions listed in Table 1). The area of each box denotes the number of sources. Bottom: Single exposure spectral grasp of each instrument, with IGRINS being $\sim 1\mu$m. Wavelengths listed are the full wavelength range accessible by the instrument, with iSHELL,[31] NIRSPEC,[30] and CRIRES(+)[32,43] requiring multiple settings to cover all possible wavelengths.

Table 1. Assumptions for Instrument Comparisons in Figures 1 & 2

Instrument/Facility	Resolution	FWHM^a	K-band limit	References
IGRINS/McDonald (2.7m)	45,000	1.″0	11.10	23
IGRINS/DCT (4.3m)	45,000	0.″8	11.15	This Paper
IGRINS/Gemini (8.1m)	45,000	0.″6	11.85	This Paper
iSHELL/IRTF (3.2m)	37,500	–	10.5	b,44
GIANO/TNG (3.58m)	50,000	–	9.5	c,45
SPIRou/CFHT (3.58m)	70,000	–	12.1	d,46
CRIRES/VLT (8.2m)	50,000	–	10.2	e,32
CRIRES+/VLT (8.2m)	50,000	–	10.2	47
NIRSPEC/Keck (10m)	18,750	–	10.6	f,30
NIRSPEC-Upgrade/Keck (10m)	37,500	–	11.8	48, 49
GMTNIRS/GMT (24.5m)	65,000	0.″6	15.5	50, 51

All limiting magnitudes assume 3600s of exposure time, SNR=100, airmass <2, and typical seeing for each site.
a) Default Exposure Time Calculator (ETC) or slit-width FWHM values used when not listed.
b) http://irtfweb.ifa.hawaii.edu/~ishell/
c) http://www.tng.iac.es/instruments/giano/
d) http://www.cfht.hawaii.edu/Instruments/SPIRou/SPIRou_etc.php
e) ETC Legacy version P95-phase2 (December 2014)
f) https://www2.keck.hawaii.edu/inst/nirspec/

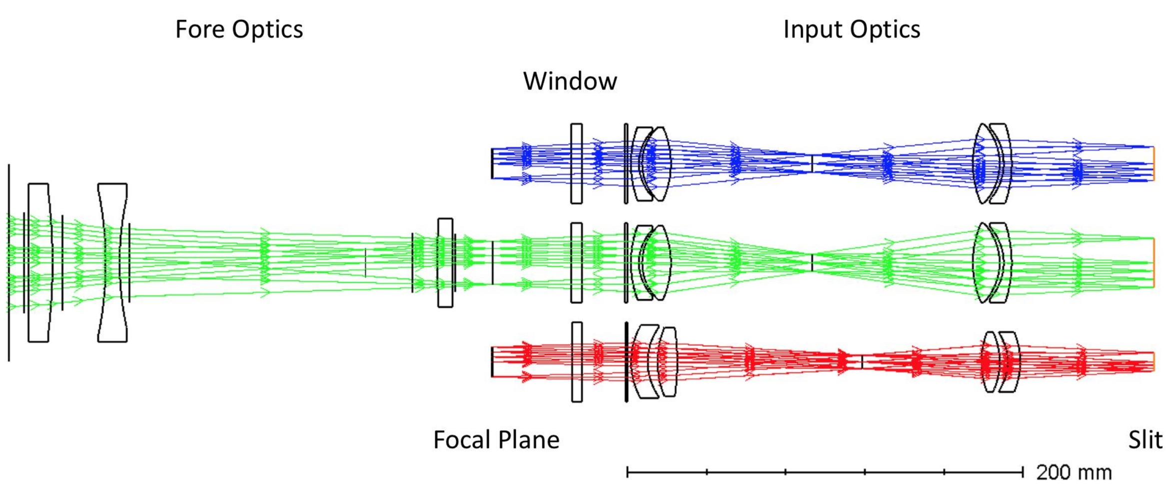

Figure 3 Input and fore optic assemblies for IGRINS at each facility with component properties listed in Table 2. The cryostat window, focal plane, and slit mask are unchanged in each layout. Top: Default input optics for the HJST at McDonald Observatory. Middle: DCT fore optics along with the default input optics. Bottom: Replacement input optics for Gemini South.

Table 2. Input and Fore Optic Parameters

Component	Default	DCT	Gemini South
Fore Optics (FO)			
FO-L1	–	S-FTM16	–
Diameter (mm)	–	80.0	–
Curvature (mm)	–	Plano / -279.9	–
FO-L2	–	S-FPL53	–
Diameter (mm)	–	80.0	–
Curvature (mm)	–	-181.3 / 148.8	–
FO-L3	–	S-FTM16	–
Diameter (mm)	–	45.0	–
Curvature (mm)	–	257.2 / Plano	–
Focal Plane			
Warm Window	ZnSe , Plano		
Input Optics (IO)			
Cold Window		Sapphire	Sapphire
Diameter (mm)		40.0	37.0
Curvature (mm)		Plano	Plano
IO-L1		S-FTM16	S-FTM16
Diameter (mm)		37.0	37.0
Curvature (mm)		54.30 / 23.78	37.82 / 30.23
IO-L2		CAF2	CAF2
Diameter (mm)		37.0	37.0
Curvature (mm)		25.51/ -44.46	45.77 / -123.42
Cold Stop Clear Aperture (mm)		8.82	7.28
IO-L3		CAF2	CAF2
Diameter (mm)		40.0	30.0
Curvature (mm)		50.44 / -29.30	42.41 / -35.48
IO-L4		S-FTM16	S-FTM16
Diameter (mm)		40.0	30.0
Curvature (mm)		-27.03 / -62.25	-26.40 / -39.51
Slit Mask			

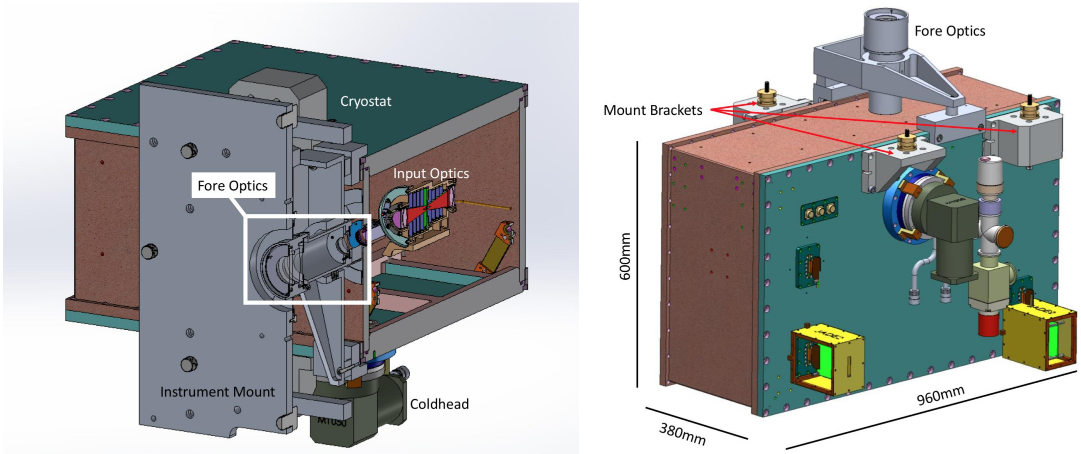

Figure 4 Left: A cutaway view of IGRINS showing the DCT mount, the fore optics and mount, and the input optics inside the cryostat. Other instrument components have been removed from this view for clarity. Right: The DCT fore-optics assembly and mount. The instrument mounting brackets are also included in this drawing.

Figure 5 IGRINS at the DCT. Top Left: The first installation of the fore optics at the DCT in 2016 September. Bottom Left: IGRINS and the glycol cooled electronics rack mounted on the DCT while pointed at the zenith. Right: IGRINS mounted without the electronics rack, immediately after the first installation, while the telescope is pointed at the horizon.

immediately behind the cryostat window and is comprised of a cold window, a pupil stop and four lenses. For the f/6.1 beam of the DCT a three element fore-optic assembly (focal extender) was designed to reproduce the required f/8.8 beam and the placement of the telescope focal plane 40mm in front of the cryostat window. Figure 4 shows a cutaway view of IGRINS with the DCT mount and fore optics installed. The lenses for the fore optics were fabricated and tested in Korea, with the full assembly built at UT Austin in 2016 August during the readiness review meeting.[†] Adjustment of the fore-optic assembly in its mount is facilitated by a v-groove and set screws, which ensure three lines of contact and maintain alignment of the optics with the window when setting the distance between the optics and the cryostat window. In Figure 5 the IGRINS postdoc, Dr. Kimberly Sokal (UT Austin), installed the DCT fore optics for the first time at the DCT while Dr. Lisa Prato (Lowell Observatory) looks on.

To make room for the DCT fore optics, the IGRINS calibration unit had to be removed. Initial instrument characterization employed the calibration unit to provide internal flat and arc lamp spectra. We continued to use the calibration unit for the first two years that IGRINS was at McDonald Observatory. Once on the DCT, we fully switched to dome flat-field lamps and sky emission and absorption features for wavelength calibration. This was possible because the IGRINS echellograms are unchanged.[3] The IGRINS calibration unit was no longer used at any facility once the observing and data reduction procedures were updated in late-2016.

Mechanical modifications to IGRINS for the DCT were all external to the cryostat. The instrument mount connects to IGRINS with four brackets, which are shown attached to the cryostat in Figure 4. Three of the brackets define the instrument plane and the fourth bracket only retains the instrument. The part of the mount that interfaces with the DCT instrument cube is a plate with a 150 mm port, which was baffled to prevent light leakage into the cube. An additional requirement for the DCT mount was that it had to be used to lift IGRINS from its transportation cart, on the dome floor, to the telescope for installation. Between the first and second visit to the DCT the instrument mount was remade to position the optimal focus for IGRINS near the center of the telescope focal range.

On the HJST IGRINS had an air-cooled electronics rack that was co-mounted with IGRINS.[2] For the DCT a new rack was built to provide glycol cooling to the electronics and reduce the thermal load on the instrument cube. This larger electronics rack also needed its own mount next to IGRINS on the DCT without overflowing the instrument envelope. Figure 5 shows both IGRINS immediately after installation, with the telescope at the horizon, and with the electronics rack mounted next to it.

IGRINS on the DCT also required consideration for utilities and software interfaces. DCT instrument patch panels provide uninterruptible power, helium and glycol coolant, and fiber network connections between the telescope and the control room. In addition to these services, a Brooks 9600 Helium compressor was installed on the ground floor of the telescope and a coldhead power cable was routed from the compressor to the instrument cube. Facility modifications for IGRINS included a new (and later modified) lifting fixture for instrument installation and the testing and stabilization of compressed-helium hoses for the CTI Cryogenics 1050C coldhead. Additionally, IGRINS motivated the connection of the facility glycol cooling system to emergency power to ensure uninterrupted cooling to the IGRINS helium compressor in the event of mains power loss. The TCS proxy was a new software interface that worked as an intermediary between between existing IGRINS control software (developed by Kyung Hee University and KASI) and the Telescope Control System (TCS). Since the DCT continuously publishes facility status as XML-based updates,[53] the primary role of the TCS-proxy is to read the required XML elements, populate FITS headers, and send offset commands from the instrument user interfaces to the TCS. The TCS proxy was developed while considering a future visit to Gemini South.

2.2 Performance at the DCT

The primary improvement provided by the DCT was the pointing and tracking stability of the telescope while observing with IGRINS. Facility guiding is available at the DCT, but IGRINS observers generally used the slit-viewing camera to acquire targets and guide. Commissioning tests verified absolute pointing accuracy to within 10 arcseconds, relative pointing accuracy to within $0\farcs5$ and tracking accuracy of $<2''$ over 20 minutes. Blind

[†]A failure with lens fabrication in 2016 May delayed the delivery of the fore optics to the readiness review, just two weeks before first light on the DCT.

offsets between a reference star and extended emission targets a few arcminutes away were correct to within 0.″5. The ability to rapidly acquire and then track targets increased observing efficiency and reduced exposure times. The increase in collecting area of the DCT relative to the HJST was an improvement in good seeing conditions, in which case there was ∼1 magnitude gain in overall sensitivity.

One of the primary measures of success for astronomical instruments is observer demand. The demand for IGRINS has outpaced all other facility instruments wherever it has been. Since the initial commissioning of IGRINS in 2014, it has had approximately half (423 out of 853 nights) of the scheduled observing time at McDonald Observatory. At the DCT the fraction is slightly above half with 180 nights of use out of 338 nights installed on the telescope.

3. IGRINS AT GEMINI SOUTH

The 8.1-meter Gemini South telescope is located on Cerro Pachón in Chile and observations are made from the La Serena headquarter. The telescope generally operates in queue mode, with observations chosen by program ranking and weather conditions.[54] Many visitor instruments at Gemini are scheduled in dedicated blocks, in which the instrument team is present, while facility instruments can be used for any number of targets on any night. Given the demand for IGRINS at Gemini in 2018A (50 nights), and the immediate community access, it was scheduled in three blocks during bright time. Within these blocks, the IGRINS queue was prioritized in the same fashion as typical Gemini observing, by ranking and weather conditions, and the IGRINS Team made all observations.

The effort to visit Gemini started with the submission of a Large and Long Program proposal in 2016B (Young Star & Protoplanetary Disk Evolution with High-Resolution IR Spectroscopy, P.I. Mace). The proposal outlined a study of fainter YSOs in the Ophiuchus star forming region requiring 135 hours of time in 2018A. After being awarded these 135 hours by the NOAO Time Allocation Committee (TAC), we submitted a grant proposal to the National Science Foundation (AST-1702267, P.I. Mace) to support engineering and fabrication costs, as well as support of the community time awarded by the Gemini TAC. Funds were awarded in 2017 March, one year before installation at Gemini. Many of the adjustments to IGRINS for the DCT, and the lessons learned, were also valuable to the Gemini visit.

IGRINS returned to UT Austin at the end of 2018 January, after the second visit to the DCT. In the lab, the IGRINS coldhead was replaced with a refurbished unit (following 18 months of use) and the new input optics (Figure 3) were installed inside the cryostat. Shipping from UT to Cerro Pachón was handled by the Association of Universities for Research in Astronomy (AURA) on behalf of Gemini.[‡] After initial lab tests confirmed that IGRINS completed the trip safely, IGRINS was installed on Gemini South on 2018 March 21. Commissioning at Gemini was from 2018 April 2-8, with first light occurring on the *first night*. The first-light spectrum at Gemini, of the young star TW Hydra, is shown in Figure 6.

In preparation for the Gemini call for proposals in 2017 September we designed a proposer focused website that described the past use and capabilities of IGRINS, along with the expected sensitivities at Gemini.[§] This website will continue to be updated with instructions for proposers and the measured sensitivities in this paper. At Gemini, IGRINS had the largest number of requests for the 2018A semester and has been scheduled for 50 nights in its 3 month visit. The proprietary period for all Gemini observations is 12 months and the IGRINS observations in 2018A will be made public by 2019 July.

3.1 Modifications to IGRINS for Gemini Observatory

IGRINS visiting Gemini was considered in the original instrument design, with multiple input optic models tested without changing the optics following the slit mask. For Gemini, the input optics inside the cryostat must convert the telescope f/16 beam to f/10 at the slit. The default four-element input-optic assembly (f/8.8 to f/10) was replaced with a new four-element input optic assembly (shown in Figure 3) that was precision aligned by

[‡] The shipper in this case was DHL Global Forwarding, who contracted with American Airlines for the flight between Dallas, USA, and Santiago, Chile. IGRINS rode in the cargo hold of the passenger flight AA945 on 2018 February 28. All other legs of the trip were completed by truck.

[§] https://sites.google.com/site/igrinsatgemini/

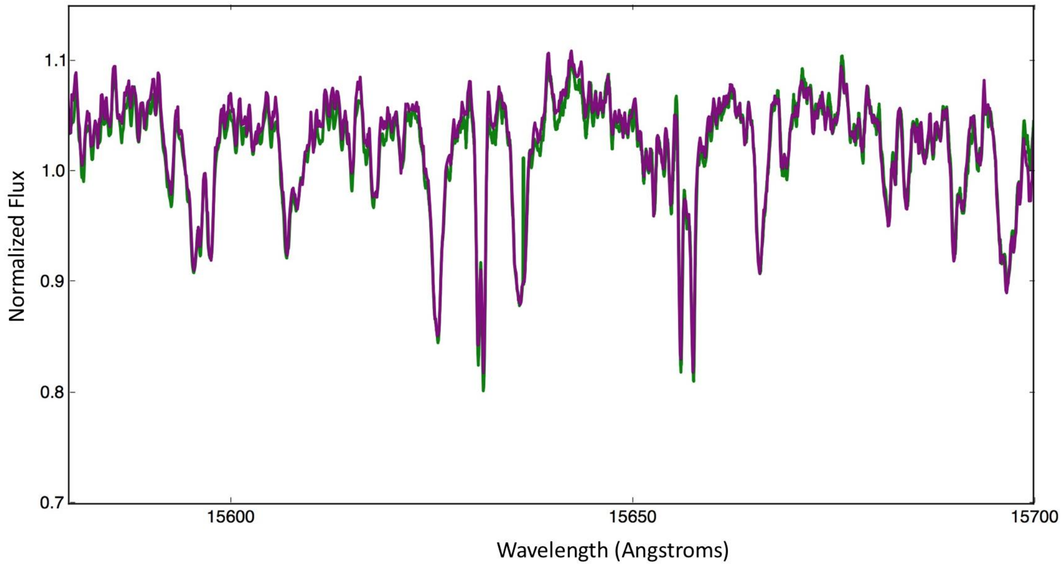

Figure 6 The first-light H-band spectrum of TW Hydra from IGRINS commissioning at Gemini on 2018 April 2 (purple line). For comparison, a combination of four observations of TW Hydra[9] from McDonald Observatory is also shown (green line). The four observations at McDonald were all made at an airmass of 2.4 and required a total exposure time of 5280 seconds. The larger collecting area, and access to southern targets (airmass<1.1 for TW Hydra), provided by Gemini South resulted in a similar spectrum but required only 240s total exposure time.

KASI in Korea. Both optical assemblies were precision fabricated so they get installed onto the same locating pins on the IGRINS optical bench. A side-by-side comparison photo of the two input-optic assemblies is shown in Figure 7. Once the Gemini input optics were installed, a USAF 1951 target was placed at the instrument focal plane (40mm in front of the window) and the image quality was verified. Figure 7 shows the pixel-limited resolution of the USAF target when imaged with the IGRINS slit-viewing camera. After validating the Gemini input optics, IGRINS was prepared for shipping.

Mechanical modifications to IGRINS for Gemini were similar to those for the DCT. However, IGRINS is a large instrument for the DCT, but on Gemini South it is one of the smaller instruments on the instrument support structure (ISS). The instrument mount for Gemini connects to IGRINS at the same four points shown in Figure 4, and interfaces with the ISS on eight pads, radially centered around the port, with four fasteners each. Additionally, the ISS flange is ∼340 mm from the cryostat window, compared to ∼270 mm at the DCT. To compensate for IGRINS' low mass, a ballast weight assembly (BWA) was installed on the same side of the ISS as IGRINS. The BWA had the added benefit of serving as the mount for the glycol cooled electronics rack. Prior to use, the BWA also had to be modified by Gemini to remove interference with the IGRINS cryostat. Figure 8 shows IGRINS and the BWA attached to the ISS following installation on Gemini.

Adjustments to IGRINS for the utilities and software interfaces at Gemini were simplified by our prior visits to the DCT. Compressed helium, chilled glycol, electrical power, and fiber-optic connections are all provided at the telescope patch panels as defined by the Gemini interface control documentation.[¶] Unlike at McDonald Observatory and the DCT, coldhead power is not supplied directly from the helium compressor and we instead used a Helix brand 3-phase power supply mounted to the BWA. The use of a stand-alone power supply introduces a failure mode where the helium compressor can turn off while the coldhead remains powered. If this were to occur then the coldhead would overheat, add heat to the cryostat, and eventually fail. This potential failure

[¶] https://www.gemini.edu/sciops/instruments/visiting-instrument-telescope-interfaces

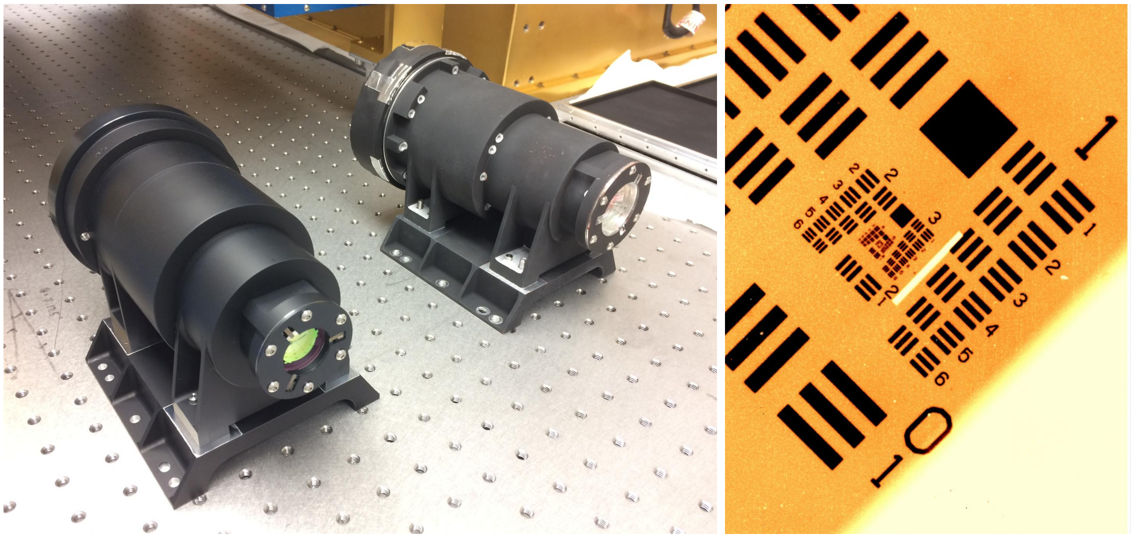

Figure 7 IGRINS input optics in the UT Austin lab. Left: The new f/16-to-f/10 input optics for Gemini (left) along with the default f/8.8-to-f/10 input optics (right). Right: The slit-viewing camera image of a USAF 1951 Test Target and the IGRINS slit (short yellow line). Resolved line spacing, limited by pixel sampling rather than optical quality, is clearly seen down to Group 4 and Element 4.

Figure 8 IGRINS at Gemini. Left: After installation the team got a photo before leaving IGRINS mounted for its 3-month visit. Right: IGRINS on the back of the Gemini South telescope.

is avoided by installing an Ashcroft P-series differential pressure switch, which was added in parallel to the coldhead helium lines, to power off the Helix power supply when the compressor stops running. The TCS proxy software written for the DCT was modified for use at Gemini and was used in tandem with the Visitor Instrument Interface software.[‖]

3.2 Performance at Gemini

The slit width for IGRINS at Gemini is $0\farcs34$. This is smaller than the typical K-band FWHM at Gemini ($\sim 0\farcs6$) and so slit-losses can be similar to the DCT. When the FWHM at Gemini is the same as the slit width, IGRINS achieves $\sim$1.5 magnitudes on the faint limit (K=12.5 mag) relative to the DCT in typical conditions. Comparison

[‖] https://www.gemini.edu/sciops/instruments/visiting/tcs_cjm_069.pdf

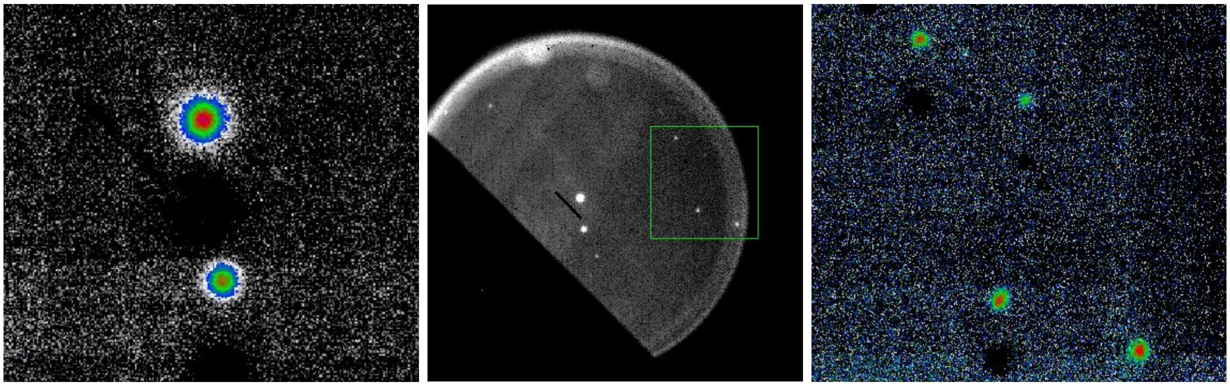

Figure 9 Center: Slit-view camera image from commissioning at Gemini. Left and Right: Sources at the middle of the field, and on the far edges, are undistorted at the seeing limit of 0.″3. The slit length at Gemini is 5″ and the slit-viewer field of view is ∼45″ in diameter.

of exposure time estimates to the measured performance for fourteen objects observed during commissioning reveals a ∼10% increase in flux above what the increase in telescope diameter alone would provide. This can be largely credited to the infrared optimized silver coating on Gemini mirrors,[55–57] but is also attributed to good facility guiding and active tip-tilt correction by the secondary mirror.

IGRINS commissioning at Gemini verified the optical quality measured in the lab (Figure 7) with seeing limited point-spread functions (PSFs) across the entire slit-viewer field of view. Figure 9 shows the full image of the slit-viewer and two background subtracted images of stars used to verify alignment and pointing during commissioning. The binary at the center of the field is HIP 38095, an A0V star and its companion with a separation of 4.″2. Their 2MASS magnitudes are K=11.6 and 12.8. At the edge of the slit-viewer there are four sources with K magnitudes between 13.5 and 15.9, which also show 0.″3 FWHM as measured on this commissioning night.

All other attributes of IGRINS science capabilities[3] have remained the same at Gemini. Comparison of the thermal background in the K-band reveals the same number of counts as was observed at McDonald and the DCT for the same ambient temperatures. Inter-order light, the result of scattered light within IGRINS, is low-level and unchanged at Gemini.

4. IGRINS IS A PROTOTYPE FOR GMTNIRS

GMTNIRS[50,51] is a high-resolution spectrograph that will cover 1.07-5.4μm in a single exposure at R=60,000 in the J, H, and K bands and R=85,000 in the L and M bands. Additionally, GMTNIRS will employ the facility adaptive optics system on the Giant Magellan Telescope[58] and have slit dimensions of approximately 0.″085×1.″35. Based on the success of IGRINS as a visitor instrument at the DCT and Gemini, and delays in the GMT schedule for fully-operational adaptive optics,[59] GMTNIRS will first be developed for a Magellan telescope[60] in partnership with the Carnegie Observatories. This early version of GMTNIRS, named MagNIFIES, will require different input optics for the two telescopes but maintain the same f/number at the slit. This is the same concept used successfully with IGRINS to move the instrument to progressively larger facilities while the instrument operations and stability are improved. Figure 10 shows the current optical path for MagNIFIES, which includes a slit-viewing camera and six spectrographs (J, H, K, L1, L2, M). The primary disperser for each spectrograph is a silicon immersion grating developed at UT Austin[37,38] and all detectors will be Teledyne H2RGs.[61] MagNIFIES, with natural seeing on a 6.5 meter telescope, will have R=39,000 in the J, H, and K bands and R=52,000 in the L and M bands with a ∼0.″4×5.″5 slit. Many of the lessons from IGRINS will translate to MagNIFIES and GMTNIRS in the coming years.

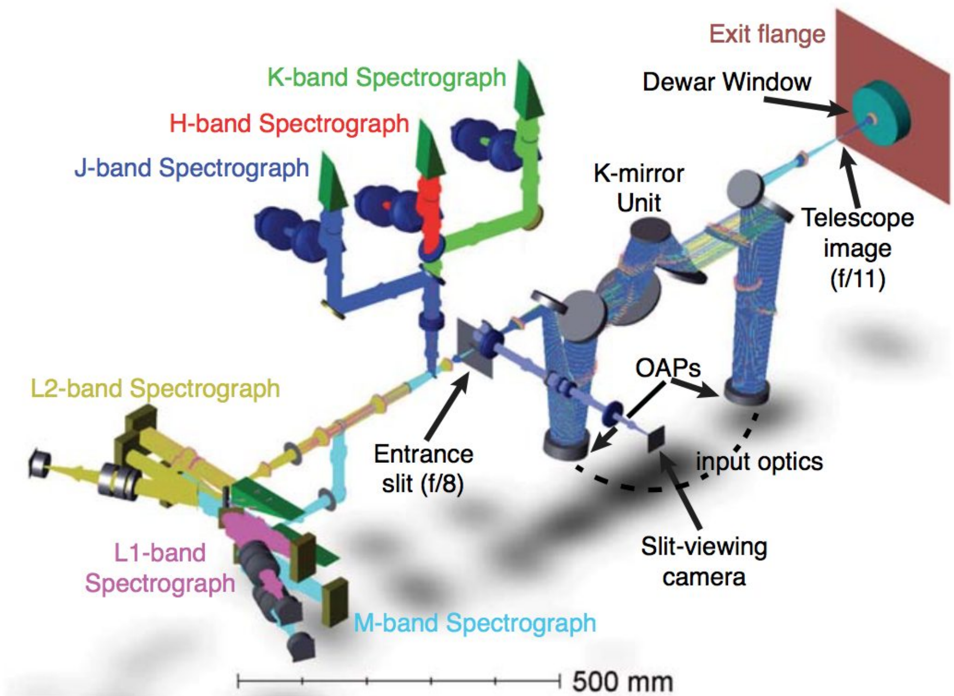

Figure 10 The optical layout of MagNIFIES. The difference between GMTNIRS and MagNIFIES will be the input optics. All the spectrograph components will remain the same, just like we have done with IGRINS as a visitor instrument at the DCT and Gemini South.

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REFERENCES

[1] Yuk, I.-S., Jaffe, D. T., Barnes, S., Chun, M.-Y., Park, C., Lee, S., Lee, H., Wang, W., Park, K.-J., Pak, S., Strubhar, J., Deen, C., Oh, H., Seo, H., Pyo, T.-S., Park, W.-K., Lacy, J., Goertz, J., Rand, J., and Gully-Santiago, M., "Preliminary design of IGRINS (Immersion GRating INfrared Spectrograph)," in

[*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735**, 1 (July 2010).

[2] Park, C., Jaffe, D. T., Yuk, I.-S., Chun, M.-Y., Pak, S., Kim, K.-M., Pavel, M., Lee, H., Oh, H., Jeong, U., Sim, C. K., Lee, H.-I., Nguyen Le, H. A., Strubhar, J., Gully-Santiago, M., Oh, J. S., Cha, S.-M., Moon, B., Park, K., Brooks, C., Ko, K., Han, J.-Y., Nah, J., Hill, P. C., Lee, S., Barnes, S., Yu, Y. S., Kaplan, K., Mace, G., Kim, H., Lee, J.-J., Hwang, N., and Park, B.-G., "Design and early performance of IGRINS (Immersion Grating Infrared Spectrometer)," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9147**, 1 (July 2014).

[3] Mace, G., Kim, H., Jaffe, D. T., Park, C., Lee, J.-J., Kaplan, K., Yu, Y. S., Yuk, I.-S., Chun, M.-Y., Pak, S., Kim, K.-M., Lee, J.-E., Sneden, C. A., Afsar, M., Pavel, M. D., Lee, H., Oh, H., Jeong, U., Park, S., Kidder, B., Lee, H.-I., Nguyen Le, H. A., McLane, J., Gully-Santiago, M., Oh, J. S., Lee, S., Hwang, N., and Park, B.-G., "300 nights of science with IGRINS at McDonald Observatory," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE,* **9908**, 99080C (Aug. 2016).

[4] Lacy, J. H., Sneden, C., Kim, H., and Jaffe, D. T., "H_2, CO, and Dust Absorption through Cold Molecular Clouds," *ApJ,* **838**, 66 (Mar. 2017).

[5] Lee, S., Lee, J.-E., Park, S., Lee, J.-J., Kidder, B., Mace, G. N., and Jaffe, D. T., "IGRINS Spectroscopy of Class I Sources: IRAS 03445+3242 and IRAS 04239+2436," *ApJ,* **826**, 179 (Aug. 2016).

[6] Herczeg, G. J., Dong, S., Shappee, B. J., Chen, P., Hillenbrand, L. A., Jose, J., Kochanek, C. S., Prieto, J. L., Stanek, K. Z., Kaplan, K., Holoien, T. W.-S., Mairs, S., Johnstone, D., Gully-Santiago, M., Zhu, Z., Smith, M. C., Bersier, D., Mulders, G. D., Filippenko, A. V., Ayani, K., Brimacombe, J., Brown, J. S., Connelley, M., Harmanen, J., Itoh, R., Kawabata, K. S., Maehara, H., Takata, K., Yuk, H., and Zheng, W., "The Eruption of the Candidate Young Star ASASSN-15QI," *ApJ,* **831**, 133 (Nov. 2016).

[7] Gully-Santiago, M. A., Herczeg, G. J., Czekala, I., Somers, G., Grankin, K., Covey, K. R., Donati, J. F., Alencar, S. H. P., Hussain, G. A. J., Shappee, B. J., Mace, G. N., Lee, J.-J., Holoien, T. W.-S., Jose, J., and Liu, C.-F., "Placing the Spotted T Tauri Star LkCa 4 on an HR Diagram," *ApJ,* **836**, 200 (Feb. 2017).

[8] Lyo, A.-R., Kim, J., Lee, J.-J., Kim, K.-H., Kang, J., Byun, D.-Y., Mace, G., Sokal, K. R., Park, C., Chun, M.-Y., Oh, H., Yu, Y. S., Sok Oh, J., Jeong, U., Kim, H., Pak, S., Hwang, N., Park, B.-G., Lee, S., Kaplan, K., Lee, H.-I., Nguyen Le, H. A., Jaffe, D., and Friends of AASTeX Collaboration, "Inner Warm Disk of ESO Hα 279a Revealed by NA I and CO Overtone Emission Lines," *ApJ,* **844**, 4 (July 2017).

[9] Sokal, K. R., Deen, C. P., Mace, G. N., Lee, J.-J., Oh, H., Kim, H., Kidder, B. T., and Jaffe, D. T., "Characterizing TW Hydra," *ApJ,* **853**, 120 (Feb. 2018).

[10] Oh, H., Pyo, T.-S., Yuk, I.-S., Park, B.-G., Park, C., Chun, M.-Y., Pak, S., Kim, K.-M., Sok Oh, J., Jeong, U., Yu, Y. S., Lee, J.-J., Kim, H., Hwang, N., Kaplan, K., Pavel, M., Mace, G., Lee, H.-I., Nguyen Le, H. A., Lee, S., and Jaffe, D. T., "IGRINS Near-IR High-resolution Spectroscopy of Multiple Jets around LkHα 234," *ApJ,* **817**, 148 (Feb. 2016).

[11] Oh, H., Pyo, T.-S., Kaplan, K., Yuk, I.-S., Park, B.-G., Mace, G., Park, C., Chun, M.-Y., Pak, S., Kim, K.-M., Sok Oh, J., Jeong, U., Yu, Y. S., Lee, J.-J., Kim, H., Hwang, N., Lee, H.-I., Nguyen Le, H. A., Lee, S., and Jaffe, D. T., "Three-dimensional Shock Structure of the Orion KL Outflow with IGRINS," *ApJ,* **833**, 275 (Dec. 2016).

[12] Le, H. A. N., Pak, S., Kaplan, K., Mace, G., Lee, S., Pavel, M., Jeong, U., Oh, H., Lee, H.-I., Chun, M.-Y., Yuk, I.-S., Pyo, T.-S., Hwang, N., Kim, K.-M., Park, C., Sok Oh, J., Yu, Y. S., Park, B.-G., Minh, Y. C., and Jaffe, D. T., "Fluorescent H_2 Emission Lines from the Reflection Nebula NGC 7023 Observed with IGRINS," *ApJ,* **841**, 13 (May 2017).

[13] Kaplan, K. F., Dinerstein, H. L., Oh, H., Mace, G. N., Kim, H., Sokal, K. R., Pavel, M. D., Lee, S., Pak, S., Park, C., Sok Oh, J., and Jaffe, D. T., "Excitation of Molecular Hydrogen in the Orion Bar Photodissociation Region from a Deep Near-infrared IGRINS Spectrum," *ApJ,* **838**, 152 (Apr. 2017).

[14] Oh, H., Pyo, T.-S., Koo, B.-C., Yuk, I.-S., Kaplan, K. F., Lee, Y.-H., Sokal, K. R., Mace, G. N., Park, C., Lee, J.-J., Park, B.-G., Hwang, N., Kim, H., and Jaffe, D. T., "High-resolution Near-IR Spectral Mapping with H_2 and [Fe II] Lines of Multiple Outflows around LkHα 234," *ApJ,* **858**, 23 (May 2018).

[15] Sterling, N. C., Dinerstein, H. L., Kaplan, K. F., and Bautista, M. A., "Discovery of Rubidium, Cadmium, and Germanium Emission Lines in the Near-infrared Spectra of Planetary Nebulae," *ApJ,* **819**, L9 (Mar. 2016).

[16] Sneden, C., Afsar, M., Jaffe, D. T., Kim, H., and Mace, G., "An Infrared High Resolution Spectroscopic Abundance Study of the Metal-Poor Giant HD 122563," in [*American Astronomical Society Meeting Abstracts*], *American Astronomical Society Meeting Abstracts* **225**, #342.11 (Jan. 2015).

[17] Afşar, M., Bozkurt, Z., Böcek Topçu, G., Şehitoğlu, G., Sneden, C., Jaffe, D., Kim, H., and Mace, G., "High-Resolution Near Infrared Observations of Red Horizontal Branch Stars in the Galactic Field," in [*EAS Publications Series*], *EAS Publications Series* **71**, 347–348 (Dec. 2015).

[18] Afşar, M., Sneden, C., Frebel, A., Kim, H., Mace, G. N., Kaplan, K. F., Lee, H.-I., Oh, H., Sok Oh, J., Pak, S., Park, C., Pavel, M. D., Yuk, I.-S., and Jaffe, D. T., "The Chemical Compositions of Very Metal-poor Stars HD 122563 and HD 140283: A View from the Infrared," *ApJ,* **819**, 103 (Mar. 2016).

[19] Johns-Krull, C. M., McLane, J. N., Prato, L., Crockett, C. J., Jaffe, D. T., Hartigan, P. M., Beichman, C. A., Mahmud, N. I., Chen, W., Skiff, B. A., Cauley, P. W., Jones, J. A., and Mace, G. N., "A Candidate Young Massive Planet in Orbit around the Classical T Tauri Star CI Tau," *ApJ,* **826**, 206 (Aug. 2016).

[20] Mace, G. N., Mann, A. W., Skiff, B. A., Sneden, C., Kirkpatrick, J. D., Schneider, A. C., Kidder, B., Gosnell, N. M., Kim, H., Mulligan, B. W., Prato, L., and Jaffe, D., "Wolf 1130: A Nearby Triple System Containing a Cool, Ultramassive White Dwarf," *ApJ,* **854**, 145 (Feb. 2018).

[21] Mann, A. W., Gaidos, E., Mace, G. N., Johnson, M. C., Bowler, B. P., LaCourse, D., Jacobs, T. L., Vanderburg, A., Kraus, A. L., Kaplan, K. F., and Jaffe, D. T., "Zodiacal Exoplanets in Time (ZEIT). I. A Neptune-sized Planet Orbiting an M4.5 Dwarf in the Hyades Star Cluster," *ApJ,* **818**, 46 (Feb. 2016).

[22] Mann, A. W., Newton, E. R., Rizzuto, A. C., Irwin, J., Feiden, G. A., Gaidos, E., Mace, G. N., Kraus, A. L., James, D. J., Ansdell, M., Charbonneau, D., Covey, K. R., Ireland, M. J., Jaffe, D. T., Johnson, M. C., Kidder, B., and Vanderburg, A., "Zodiacal Exoplanets in Time (ZEIT). III. A Short-period Planet Orbiting a Pre-main-sequence Star in the Upper Scorpius OB Association," *AJ,* **152**, 61 (Sept. 2016).

[23] Mann, A. W., Gaidos, E., Vanderburg, A., Rizzuto, A. C., Ansdell, M., Medina, J. V., Mace, G. N., Kraus, A. L., and Sokal, K. R., "Zodiacal Exoplanets in Time (ZEIT). IV. Seven Transiting Planets in the Praesepe Cluster," *AJ,* **153**, 64 (Feb. 2017).

[24] Robinson, E. L., Froning, C. S., Jaffe, D. T., Kaplan, K. F., Kim, H., Mace, G. N., Sokal, K. R., and Lee, J.-J., "The Spectrum of SS 433 in the H and K Bands," *ApJ,* **841**, 79 (June 2017).

[25] Rappaport, S., Vanderburg, A., Borkovits, T., Kalomeni, B., Halpern, J. P., Ngo, H., Mace, G. N., Fulton, B. J., Howard, A. W., Isaacson, H., Petigura, E. A., Mawet, D., Kristiansen, M. H., Jacobs, T. L., LaCourse, D., Bieryla, A., Forgács-Dajka, E., and Nelson, L., "EPIC 220204960: A Quadruple Star System Containing Two Strongly Interacting Eclipsing Binaries," *MNRAS,* **467**, 2160–2179 (May 2017).

[26] Bowler, B. P., Kraus, A. L., Bryan, M. L., Knutson, H. A., Brogi, M., Rizzuto, A. C., Mace, G. N., Vanderburg, A., Liu, M. C., Hillenbrand, L. A., and Cieza, L. A., "The Young Substellar Companion ROXs 12 B: Near-infrared Spectrum, System Architecture, and Spin-Orbit Misalignment," *AJ,* **154**, 165 (Oct. 2017).

[27] Han, E., Muirhead, P. S., Swift, J. J., Baranec, C., Law, N. M., Riddle, R., Atkinson, D., Mace, G. N., and DeFelippis, D., "Magnetic Inflation and Stellar Mass. I. Revised Parameters for the Component Stars of the Kepler Low-mass Eclipsing Binary T-Cyg1-12664," *AJ,* **154**, 100 (Sept. 2017).

[28] Kesseli, A. Y., Muirhead, P. S., Mann, A. W., and Mace, G., "Magnetic Inflation and Stellar Mass. II. On the Radii of Single, Rapidly Rotating, Fully Convective M-Dwarf Stars," *AJ,* **155**, 225 (June 2018).

[29] Mann, A. W., Vanderburg, A., Rizzuto, A. C., Kraus, A. L., Berlind, P., Bieryla, A., Calkins, M. L., Esquerdo, G. A., Latham, D. W., Mace, G. N., Morris, N. R., Quinn, S. N., Sokal, K. R., and Stefanik, R. P., "Zodiacal Exoplanets in Time (ZEIT). VI. A Three-planet System in the Hyades Cluster Including an Earth-sized Planet," *AJ,* **155**, 4 (Jan. 2018).

[30] McLean, I. S., Becklin, E. E., Bendiksen, O., Brims, G., Canfield, J., Figer, D. F., Graham, J. R., Hare, J., Lacayanga, F., Larkin, J. E., Larson, S. B., Levenson, N., Magnone, N., Teplitz, H., and Wong, W., "Design and development of NIRSPEC: a near-infrared echelle spectrograph for the Keck II telescope," in [*Infrared Astronomical Instrumentation*], Fowler, A. M., ed., *Proc. SPIE,* **3354**, 566–578 (Aug. 1998).

[31] Rayner, J., Bond, T., Bonnet, M., Jaffe, D., Muller, G., and Tokunaga, A., "iSHELL: a 1-5 micron cross-dispersed R=70,000 immersion grating spectrograph for IRTF," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], *Proc. SPIE,* **8446**, 84462C (Sept. 2012).

[32] Kaeufl, H.-U., Ballester, P., Biereichel, P., Delabre, B., Donaldson, R., Dorn, R., Fedrigo, E., Finger, G., Fischer, G., Franza, F., Gojak, D., Huster, G., Jung, Y., Lizon, J.-L., Mehrgan, L., Meyer, M., Moorwood, A., Pirard, J.-F., Paufique, J., Pozna, E., Siebenmorgen, R., Silber, A., Stegmeier, J., and Wegerer, S., "CRIRES: a high-resolution infrared spectrograph for ESO's VLT," in [*Ground-based Instrumentation for Astronomy*], Moorwood, A. F. M. and Iye, M., eds., *Proc. SPIE,* **5492**, 1218–1227 (Sept. 2004).

[33] Le, H. A. N., Pak, S., Jaffe, D. T., Kaplan, K., Lee, J.-J., Im, M., and Seifahrt, A., "Exposure time calculator for Immersion Grating Infrared Spectrograph: IGRINS," *Advances in Space Research* **55**, 2509–2518 (June 2015).

[34] Marsh, J. P., Mar, D. J., and Jaffe, D. T., "Production and evaluation of silicon immersion gratings for infrared astronomy," *Appl Opt.,* **46**, 3400–3416 (June 2007).

[35] Wang, W., Gully-Santiago, M., Deen, C., Mar, D. J., and Jaffe, D. T., "Manufacturing of silicon immersion gratings for infrared spectrometers," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7739**, 4 (July 2010).

[36] Gully-Santiago, M., Wang, W., Deen, C., and Jaffe, D., "Near-infrared metrology of high-performance silicon immersion gratings," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8450**, 2 (Sept. 2012).

[37] Brooks, C., "Process improvements in the production of silicon immersion gratings," in [*Coatings, Filters and Gratings I*], *Proc. SPIE,* **9912** (Sept. 2016).

[38] Kidder, B., "Approaching perfection in the manufacturing of silicon immersion gratings," in [*Coatings, Filters and Gratings I*], *Proc. SPIE,* **9912** (Sept. 2016).

[39] Frey, B. J., Leviton, D. B., and Madison, T. J., "Temperature-dependent refractive index of silicon and germanium," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Proc. SPIE,* **6273**, 62732J (June 2006).

[40] Levine, S. E. and DeGroff, W. T., "Status and imaging performance of Lowell Observatory's Discovery Channel Telescope in its first year of full science operations," in [*Ground-based and Airborne Telescopes VI*], *Proc. SPIE,* **9906**, 990621 (Aug. 2016).

[41] Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., Huchra, J., Liebert, J., Lonsdale, C., Monet, D. G., Price, S., Seitzer, P., Jarrett, T., Kirkpatrick, J. D., Gizis, J. E., Howard, E., Evans, T., Fowler, J., Fullmer, L., Hurt, R., Light, R., Kopan, E. L., Marsh, K. A., McCallon, H. L., Tam, R., Van Dyk, S., and Wheelock, S., "The Two Micron All Sky Survey (2MASS)," *AJ,* **131**, 1163–1183 (Feb. 2006).

[42] Cutri, R. M., Skrutskie, M. F., van Dyk, S., Beichman, C. A., Carpenter, J. M., Chester, T., Cambresy, L., Evans, T., Fowler, J., Gizis, J., Howard, E., Huchra, J., Jarrett, T., Kopan, E. L., Kirkpatrick, J. D., Light, R. M., Marsh, K. A., McCallon, H., Schneider, S., Stiening, R., Sykes, M., Weinberg, M., Wheaton, W. A., Wheelock, S., and Zacarias, N., [*2MASS All Sky Catalog of point sources.*] (June 2003).

[43] Dorn, R. J., Follert, R., Bristow, P., Cumani, C., Eschbaumer, S., Grunhut, J., Haimerl, A., Hatzes, A., Heiter, U., Hinterschuster, R., Ives, D. J., Jung, Y., Kerber, F., Klein, B., Lavaila, A., Lizon, J. L., Löwinger, T., Molina-Conde, I., Nicholson, B., Marquart, T., Oliva, E., Origlia, L., Pasquini, L., Paufique, J., Piskunov, N., Reiners, A., Seemann, U., Stegmeier, J., Stempels, E., and Tordo, S., "The "+" for CRIRES: enabling better science at infrared wavelength and high spectral resolution at the ESO VLT," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE,* **9908**, 99080I (Aug. 2016).

[44] Rayner, J., Tokunaga, A., Jaffe, D., Bonnet, M., Ching, G., Connelley, M., Kokubun, D., Lockhart, C., and Warmbier, E., "iSHELL: a construction, assembly and testing," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE,* **9908**, 990884 (Aug. 2016).

[45] Origlia, L., Oliva, E., Baffa, C., Falcini, G., Giani, E., Massi, F., Montegriffo, P., Sanna, N., Scuderi, S., Sozzi, M., Tozzi, A., Carleo, I., Gratton, R., Ghinassi, F., and Lodi, M., "High resolution near IR spectroscopy with GIANO-TNG," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Proc. SPIE,* **9147**, 91471E (July 2014).

[46] Artigau, É., Kouach, D., Donati, J.-F., Doyon, R., Delfosse, X., Baratchart, S., Lacombe, M., Moutou, C., Rabou, P., Parès, L. P., Micheau, Y., Thibault, S., Reshetov, V. A., Dubois, B., Hernandez, O., Vallée, P., Wang, S.-Y., Dolon, F., Pepe, F. A., Bouchy, F., Striebig, N., Hénault, F., Loop, D., Saddlemyer, L., Barrick, G., Vermeulen, T., Dupieux, M., Hébrard, G., Boisse, I., Martioli, E., Alencar, S. H. P., do Nascimento, J.-D., and Figueira, P., "SPIRou: the near-infrared spectropolarimeter/high-precision velocimeter for the Canada-France-Hawaii telescope," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Proc. SPIE,* **9147**, 914715 (July 2014).

[47] Follert, R., Dorn, R. J., Oliva, E., Lizon, J. L., Hatzes, A., Piskunov, N., Reiners, A., Seemann, U., Stempels, E., Heiter, U., Marquart, T., Lockhart, M., Anglada-Escude, G., Löwinger, T., Baade, D., Grunhut, J., Bristow, P., Klein, B., Jung, Y., Ives, D. J., Kerber, F., Pozna, E., Paufique, J., Kaeufl, H. U., Origlia, L., Valenti, E., Gojak, D., Hilker, M., Pasquini, L., Smette, A., and Smoker, J., "CRIRES+: a cross-dispersed high-resolution infrared spectrograph for the ESO VLT," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Proc. SPIE,* **9147**, 914719 (July 2014).

[48] Martin, E. C., Fitzgerald, M. P., McLean, I. S., Adkins, S. M., Aliado, T., Brims, G., Johnson, C., Magnone, K., Wang, E., and Weiss, J., "Performance modeling of an upgraded NIRSPEC on Keck," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Proc. SPIE,* **9147**, 914781 (Aug. 2014).

[49] Martin, E. C., Fitzgerald, M. P., McLean, I. S., Kress, E., and Wang, E., "Optical design of the slit-viewing camera for the NIRSPEC upgrade," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE,* **9908**, 99082R (Aug. 2016).

[50] Jaffe, D. T., Barnes, S., Brooks, C., Gully-Santiago, M., Pak, S., Park, C., and Yuk, I., "GMTNIRS (Giant Magellan Telescope Near-Infrared Spectrograph): optimizing the design for maximum science productivity and minimum risk," in [*Ground-based and Airborne Instrumentation for Astronomy V*], *Proc. SPIE,* **9147**, 914722 (July 2014).

[51] Jaffe, D., "GMTNIRS: progress toward the Giant Magellan Telescope near- infrared spectrograph," in [*Instruments for Extremely Large Telescopes II*], *Proc. SPIE,* **9908** (Sept. 2016).

[52] DeGroff, W. T., Levine, S. E., Bida, T. A., Cornelius, F., Collins, P. L., Dunham, E. W., Hardesty, B., Lacasse, M., Sweaton, M., Venetiou, A. J., Zoonemat Kermani, S., Massey, P., Foley, M. L., Larson, H., Sanborn, J., Strosahl, S., Winner, R., and Pugh, T., "Status and performance of the Discovery Channel Telescope from commissioning into early science operations," in [*Ground-based and Airborne Telescopes V*], *Proc. SPIE,* **9145**, 91452C (July 2014).

[53] Lacasse, M. and Lotz, P. J., "Discovery Channel Telescope software progress report: addressing early commissioning and operations challenges," in [*Software and Cyberinfrastructure for Astronomy III*], *Proc. SPIE,* **9152**, 915205 (July 2014).

[54] Rutten, R., Adamson, A., and Leggett, S., "Science operations at Gemini Observatory," in [*Observatory Operations: Strategies, Processes, and Systems VI*], *Proc. SPIE,* **9910**, 99101M (July 2016).

[55] Boccas, M., Vucina, T., Araya, C., Vera, E., and Ahhee, C., "Coating the 8-m Gemini telescopes with protected silver," in [*Optical Fabrication, Metrology, and Material Advancements for Telescopes*], Atad-Ettedgui, E. and Dierickx, P., eds., *Proc. SPIE,* **5494**, 239–253 (Sept. 2004).

[56] Vucina, T., Boccas, M., Araya, C., and Ahhee, C., "Gemini's protected silver coatings: first two years in operation," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Proc. SPIE,* **6273**, 62730W (June 2006).

[57] Schneider, T., Vucina, T., Ah Hee, C., Araya, C., and Moreno, C., "The Gemini Observatory protected silver coating: ten years in operation," in [*Ground-based and Airborne Telescopes VI*], *Proc. SPIE,* **9906**, 990632 (July 2016).

[58] Jacoby, G. H., Bernstein, R., Bouchez, A., Colless, M., Crane, J., DePoy, D., Espeland, B., Hare, T., Jaffe, D., Lawrence, J., Marshall, J., McGregor, P., Shectman, S., Sharp, R., Szentgyorgyi, A., Uomoto, A., and Walls, B., "Instrumentation progress at the Giant Magellan Telescope project," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE,* **9908**, 99081U (Aug. 2016).

[59] Bouchez, A. H., Acton, D. S., Biasi, R., Conan, R., Espeland, B., Esposito, S., Filgueira, J., Gallieni, D., McLeod, B. A., Pinna, E., Santoro, F., Trancho, G., and van Dam, M. A., "The Giant Magellan Telescope adaptive optics program," in [*Adaptive Optics Systems IV*], *Proc. SPIE,* **9148**, 91480W (July 2014).

[60] Shectman, S. A. and Johns, M., "The Magellan Telescopes," in [*Large Ground-based Telescopes*], Oschmann, J. M. and Stepp, L. M., eds., *Proc. SPIE,* **4837**, 910–918 (Feb. 2003).

[61] Blank, R., Anglin, S., Beletic, J. W., Bhargava, S., Bradley, R., Cabelli, C. A., Chen, J., Cooper, D., Demers, R., Eads, M., Farris, M., Lavelle, W., Luppino, G., Moore, E., Piquette, E., Ricardo, R., Xu, M., and Zandian, M., "H2RG focal plane array and camera performance update," in [*High Energy, Optical, and Infrared Detectors for Astronomy V*], *Proc. SPIE,* **8453**, 845310 (July 2012).