PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

GMTNIRS: progress toward the Giant Magellan Telescope near-infrared spectrograph

Jaffe, Daniel, Barnes, Stuart, Brooks, Cynthia, Lee, Hanshin, Mace, Gregory, et al.

Daniel T. Jaffe, Stuart Barnes, Cynthia Brooks, Hanshin Lee, Gregory Mace, Soojong Pak, Byeong-Gon Park, Chan Park, "GMTNIRS: progress toward the Giant Magellan Telescope near-infrared spectrograph," Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 990821 (9 August 2016); doi: 10.1117/12.2232994

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

GMTNIRS: progress toward the Giant Magellan Telescope Near-Infrared Spectrograph

Daniel T. Jaffe[*a], Stuart Barnes[b], Cynthia Brooks[a], Hanshin Lee[a], Gregory Mace[a], Soojong Pak[c], Byeong-Gon Park[d], and Chan Park[d]

[a]Department of Astronomy and McDonald Observatory, University of Texas at Austin, C1400 University of Texas, Austin TX 78712;
[b]Stuart Barnes Optical Design, Germany, stuart.ian.barnes@gmail.com;
[c]School of Space Research, Kyung Hee University, 1732, Deogyeong-Daero, Giheung-Gu, Yongin-Si, Gyeonggi-Do 17104, Republic of Korea;
[d]Korea Astronomy and Space Science Institute, 776 Daedeokdae-Ro Yuseong-Gu Daejeon, 34055 Republic of Korea

ABSTRACT

GMTNIRS is a first-generation instrument for the Giant Magellan Telescope. It is a high-resolution spectrograph that will cover the 1.15-5.3 μm range in a single exposure with R=60,000 in the J, H, and K bands and R=85,000 in the L and M bands. It resides on the GMT's rotating instrument platform and employs the facility adaptive optics system. The GMTNIRS design is evolving in response to emerging science problems, particularly in the area of exoplanet atmospheres. Our design revisions also derive lessons from GMTNIRS' highly successful forerunner instrument, IGRINS. Technical changes also drive evolution of the design. It has proven impractical to manufacture 200mm long immersion gratings at the necessary precision. The success of primary mirror phasing efforts has removed the need for a very wide entrance slit that we would have needed to accommodate the Airy pattern of individual segments at the shortest operating wavelengths. The high efficiency of our double-side coated JWST grisms introduces the possibility of transmissive cross-dispersers at L and M. These changes move us toward a design with almost the same R as presented in our previous work but with a much more compact physical envelope. We will report on the optimization of the instrument design with these technical changes in mind. We are also producing the critical Si immersion gratings. The grating production is well under way and includes manufacture of H and K gratings and process development for the precision needed in the J band and for the manufacture of larger gratings for the L and M band. The development of GMTNIRS is on track with the results from IGRINS and the progress in the lab giving us substantial assurance that the new instrument can meet its performance goals.

Keywords: infrared spectroscopy, immersion gratings, Giant Magellan Telescope

1. INTRODUCTION

GMTNIRS is one of the four first-generation instruments for the Giant Magellan Telescope.[1] It is a high spectral resolution spectrograph for the near-IR, optimized for sensitivity and for large spectral grasp. The main science interests of future GMTNIRS users include studies of exoplanet atmospheres, substellar objects and cool stars, young stellar objects and protostellar disks, and resolved stellar populations across the Milky Way and in nearby galaxies.

The basic intent of GMTNIRS has remained constant since the early design phase: to provide high spectral resolution over a large spectral range with significantly better sensitivity and more spectral grasp than current instruments. In its first iteration,[2] GMTNIRS was a natural seeing instrument at J, H, and K and an adaptive optics instrument at L and M. It made use of very large (300mm long) immersion gratings and reflective three-mirror anastigmat cameras. More recent

[*] E-mail:dtj@astro.as.utexas.edu , Telephone: +1 512 471-2877

Ground-based and Airborne Instrumentation for Astronomy VI, edited by Christopher J. Evans, Luc Simard, Hideki Takami
Proc. of SPIE Vol. 9908, 990821 · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2232994

versions of the instrument employ the GMT adaptive optics system as an input and have transmissive cameras for all five infrared bands.[2,3] The "modern" GMTNIRS concept features one spectrograph per atmospheric window and full simultaneous coverage of the near-IR from the silicon cut-on at 1.1 μm to 5.3 μm through a single slit. The science requirements dictate a resolving power $R=\lambda/\Delta\lambda \geq 40{,}000$ at JHK to be able to measure line profiles in most stellar photospheres and as high a resolving power as possible with a goal of R=100,000 in the L and M bands where interesting science involving interstellar molecular lines or the profiles of narrow lines in protostellar disks demands more resolving power. The instrument should have no moving parts within the spectrographs to foster greater stability, simplify operation, and make it easier to produce a hands-off data reduction pipeline.

The GMTNIRS design has evolved gradually. Both emerging science and changes in the technical landscape and the telescope design/performance drive this evolution in the instrument. One of the most important determinants of the final instrument design is the performance of and limitations on the critical enabling technology: silicon immersion gratings. This paper discusses the design changes since our 2014 SPIE paper[2] that result from recent science and technical changes and describe our plans for the design and construction of GMTNIRS.

2. DRIVERS FOR CHANGE

2.1 Science case for exoplanet spectroscopy

The main scientific driver for change is the emergence of the field of direct spectroscopy of exoplanets. This field has exploded in recent years and includes direct spectroscopy of planets on widely spaced orbits[4,5,6,7] differential spectroscopy of exoplanets during transits,[8,9] and high-resolution spectroscopy of non-transiting planets that takes advantage of the large shifts in the planetary spectrum with respect to the stellar spectrum over the course of an orbit.[10,11,12] Astrophysically, high-resolution spectroscopy in the infrared is particularly interesting. Working at IR wavelengths optimizes the relative flux of the exoplanets relative to the host star. The near-IR bands contain transitions of many important molecular species likely to be present in exoplanetary atmospheres. The line shapes that are measureable at high resolution, together with relative line strengths, provide information about key parameters of the planetary atmosphere including temperature-pressure curves, vertical abundance distributions, mixing, and isotope ratios. Observationally, a high resolution infrared spectrograph on a large telescope with a large spectral grasp greatly improves our detection capability which depends on the planet/star contrast (better in the IR), the number of detectable lines (large spectral grasp and high spectral resolution) and the ability to separate the planetary signal from the stellar line contamination and from telluric foregrounds (high spectral resolution). (Figure 1 illustrates some of the advantages of large spectral grasp in another context.) Even when only marginal detections are possible, the additional orbital information from a direct detection of the motion of the planet allows us to derive the planetary mass without a sin*i* ambiguity.[10] For transiting and non-transiting planets in closer orbits around their host stars, the large collecting area of GMT will allow us to reach the necessary high signal to noise to remove the stellar spectral signal from a much larger sample of planet/host star systems or, for a given system, provide the photons to make it possible to reach higher contrast.

With the high spatial resolution provided by adaptive optics and the discrimination possible with high spectral resolution, we should be able to take spectra of HR 8799 type planets. With the addition of nulling techniques, we can improve the contrast even further or allow observations of even fainter planets than we can investigate in other types of systems.[13] The emerging importance of the direct spectroscopy of planets has led us to factor instrument stability, scattered light levels, and instrument throughput even more heavily into our design optimization.

2.2 Confidence in mirror phasing

All spectrograph channels in GMTNIRS see the sky through a common slit. The instrument configuration circa 2014[2] called for an 80 milli-arcsecond wide slit. The choice of this relatively large slit size for a spectrograph fed by adaptive optics (twice the diffraction limit at the longest operating wavelength and seven times the diffraction limit at the shortest wavelength) had two drivers: concern about the ability of the primary mirror phasing system to maintain coherence at the short wavelengths and concern about whether the tip/tilt sensing and control loop could centroid sufficiently faint targets with enough accuracy. The individual segments, but not the entire 7-mirror telescope, are designed to be phase-coherent at the shorter operating wavelengths. We therefore specific a large slit size to permit most of the power in the system to be able to pass through the slit. As further design work and testing of prototype alignment systems has progressed, the confidence in the project of the ability to phase the entire primary has grown, obviating the need for quite such a large slit (Brian MacLeod, personal communication). With a somewhat smaller slit, we improve the resolving power at a given grating size without significantly sacrificing performance. Shrinking the slit size closer to the diffraction limit in the L and M bands does cause a small drop in throughput at 4-5 μm, but the penalty for this loss is modest since the same smaller slit also reduces the background at these wavelengths where thermal emission from the telescope and sky dominate the noise even at high spectral resolution.

2.3 Successes and lessons from IGRINS

The University of Texas and the Korea Astronomy and Space Science Institute constructed the Immersion Grating Infrared Spectrograph (IGRINS) as forerunner and technical/astronomical testbed for GMTNIRS.[14,15] We have operated IGRINS at the McDonald Observatory's 2.7m Harlan J. Smith telescope for nearly two years and produced an array of significant results across a broad range of astronomical subdisciplines.[16] IGRINS covers all of the infrared H and K bands (1.4-2.5 μm) in a single exposure at $R=\lambda/\Delta\lambda=45{,}000$. This coverage represents a significant increase in spectral grasp over existing high-resolution infrared spectrographs. On a 2.7m telescope with a large (50%) central obscuration and poor tracking performance, it has nearly comparable sensitivity to the earlier generation of high-resolution instruments operating on 8-10m class telescopes. Mace et al.[16] analyze the performance of IGRINS in more detail. Here, we consider only the lessons applicable to the design of GMTNIRS:

For a sensitive instrument, there is a great deal of interesting science beyond precision radial velocity observations of M stars. At the 2014 SPIE Astronomical Instrumentation meeting in Montreal, six teams presented designs or reports on first results from high resolution infrared instruments with broad spectral grasp (Carmenes[17]; FIRST[18], HPF[19], GIANO[20], SPIRou[21], IGRINS[15]). Apart from IGRINS, the instruments all have precision radial velocity measurements of late-type stars as a key science goal. By pushing for a clean optical design and mounting the instrument at the Cassegrain focus, IGRINS has achieved extremely good throughput. In the case of high-resolution spectroscopy, the excellent performance of modern infrared detector arrays means that throughput is the sole driver of sensitivity in many regimes and a dominant factor in sensitivity in all regimes. At 3-5 μm, where background emission from the sky and the telescope dominates the noise, higher throughput is the only way to increase the signal-to-noise ratio. For many applications in the J, H, and K bands where the science demands high signal-to-noise ratios, the low detector read noise and the detector stability that permit long integration times mean that the instrument operates frequently in the source noise limit. In this limit, higher throughput is once again the only path to improved performance. In both of these regimes, the observing time needed to reach a given signal to noise ratio scales inversely with the throughput. For observations of faint objects in the J, H, and K bands, detector read noise and dark current still strongly affect performance. When they dominate, the time needed to reach a given signal-to-noise ratio scales with the inverse of the throughput squared. The IGRINS experience has shown us that high throughput can open up a large range of interesting science problems that will not be as easily available to the instruments that have precision radial velocity as their primary technical requirement and sacrifice throughput to get it.

The initial few years of IGRINS observations have demonstrated that, beyond the throughput optimization, a number of design choices made in the IGRINS design will find resonance in our design for GMTNIRS. One of these choices flows from the single optical configuration. IGRINS has no moving parts in the spectrograph itself. With a fixed slit and fixed H and K echellograms, there is considerable scientific flexibility in the instrumental inflexibility. An unchanging system means that the same calibrations are valid for multiple users and that observers can interleave different science programs without any changeover cost. Most importantly, a single, largely invariant, pipeline program can produce science-quality data from the raw spectra. Such a pipeline is essential to promotion of a wider user base, given the significant analysis burden even for fully reduced high-resolution spectra. Figure 1 shows a small part of an IGRINS pipeline-reduced spectrum and corresponding analysis.

The broad spectral grasp of IGRINS has led the users to re-think the normal *modus operandi* for infrared spectroscopists. Previously, when using instruments like CSHELL or Phoenix either of which only covers a small snippet of the infrared spectrum in a single exposure (~λ/200 or λ/100), and to a lesser extent with CRIRES and NIRSPEC with their somewhat larger grasp, observers would choose the optimal spectral interval containing the lines most useful for their key astrophysical analysis. They would then choose the appropriate source sample to meet their particular science goals.

Many times, groups of observers would come back to the same sets of objects to observe different sets of lines to meet different astronomical objectives. With IGRINS, groups of astronomers are beginning to organize programs around a sample of interesting objects, agreeing upon a cadence, repetition rate, and signal-to-noise goal. Since all possible lines in the H and K bands are observed at once, they can then parse out the resulting data to different subgroups to meet different science objectives.

The final IGRINS lesson has been the value of the slit-viewing camera (Figure 2). Many interesting targets are obscured at optical wavelengths or lie in highly confused regions where multiple point sources and nebular emission are present. An ability to point precisely at a target with a <100 milli-arcsecond slit when the literature position may be accurate at that level can be essential. In our 2014 design, GMTNIRS relied on very stiff mechanics and the tip/tilt wavefront sensor to have any on-target imaging. Our current plans include a slit-viewing camera that would both have a larger field of view and provide for direct visual confirmation of the target's position on the slit at a relevant infrared wavelength. We expect the slit viewing plans to continue to evolve as the avalanche photodiode detectors grow in size and improve in performance since these devices may offer us a way to combine the slit viewing and tip/tilt guiding functions.

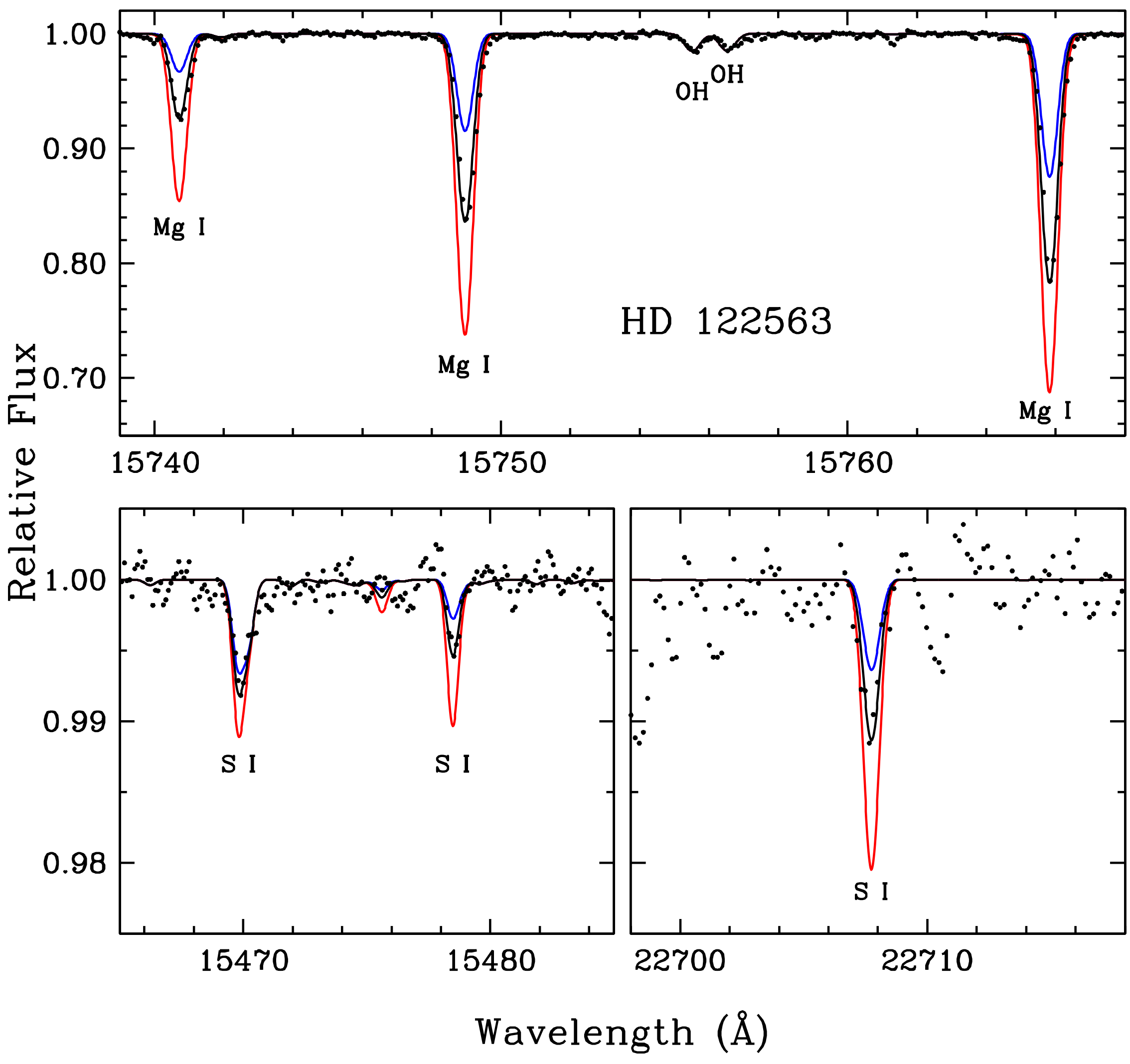

Figure 1. Selected lines and model fits from IGRINS spectra of the low-metallicity giant star HD 122563.[22] The dotted lines are the data and the solid lines are model fits with different metallicities. The Y-axis gives the fraction of the continuum. All of these high-resolution profiles come from the same spectrum and illustrate the advantage of having both high resolution and large spectral grasp.

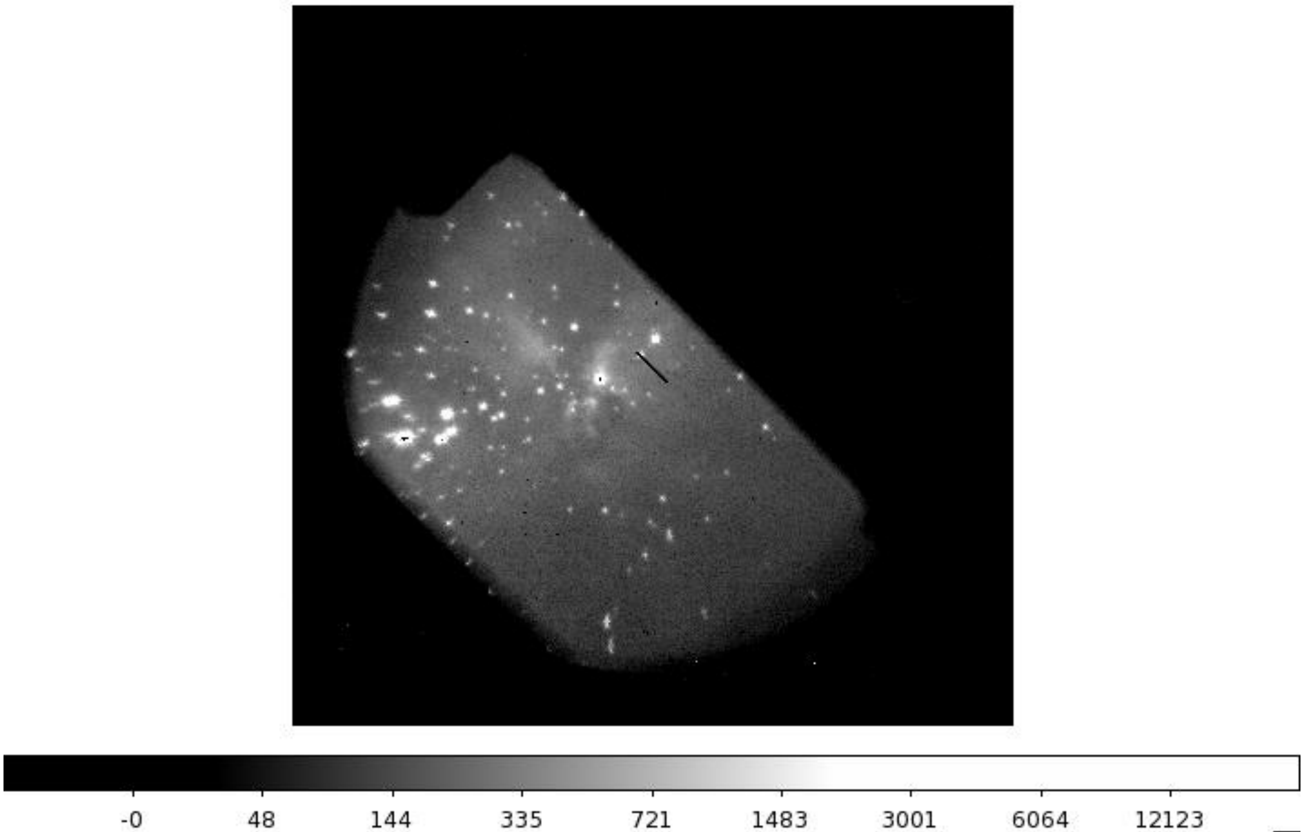

Figure 2. IGRINS slit-view camera image of the Orion Nebula. The camera operates in the K-band. Many of the objects appearing here would not be seen with a visible-light guide camera. The dark bar at the upper right is a result of light passing through the slit. The field is roughly 120x180 arcseconds across.

3. IMMERSION GRATINGS: BARRIERS AND PROGRESS

Improvements in our understanding of immersion grating production have helped shape the path of grating development for GMTNIRS and have forced a number of design changes. Our 2014 design for GMTNIRS calls for a 50 mm collimated beam at L and M. One of the key realizations of the last two years was that our 30mm thick Si disks have already pressed the silicon fabrication infrastructure, which exists around patterning and processing <1 mm thick wafers, to its limits. Any increase in thickness (necessary for an increase in collimated beam size) would require a complete retooling of the production infrastructure resulting in unacceptable cost, schedule, and performance risks. After a careful assessment, we constrained our production options to parts with a maximum thickness of 30mm.

One way to overcome the thickness barrier is to produce the grating rulings on wafers or on billets of moderate thickness and then to optically contact these wafers to polished Si prisms.[23] The high index of refraction of Si, however, puts extremely stringent constraints on the quality of the Si-Si bond. At the oblique angle at which the internal beam approaches the bonded interface, any gaps must be smaller than a few nm.[24] The chemistry of the bonding process is complex and bubbles frequently occur at the bond surface, either immediately, or in the weeks and months after bonding.[24] Bubbles with heights of only 10-20 nm can adversely affect the grating efficiency. Several attempts by our group to bond together thick billets or prisms, both in-house and with the aid of commercial specialty houses, were not satisfactory at the required level and we have abandoned pursuit of this immersion grating production method.

Once we have opted for monolithic Si immersion gratings with ~25 mm collimated beams, our remaining grating production choices involve the all-important patterning of the grating surface. We have successfully produced gratings using both electron-beam lithography[25,26] and UV contact lithography.[27] The electron beam lithography allows us to pattern slightly longer surfaces on what would be gratings with a larger value of tan(delta). At the same time, the yield of devices with both superlative surface accuracy *and* low repetitive errors has not been high and the yield becomes a significant problem when producing five gratings for the five IR bands plus appropriate spares. Our standard contact lithography process is more mature and therefore has higher yields but limits us to gratings that are about 20% shorter (~125 mm) than the longest possible e-beam patterned gratings.

Even though we have produced and fielded superlative immersion gratings in both IGRINS and iSHELL,[28] risk in the grating production remains a serious consideration. It is with this in mind that we have chosen the most robust grating production pathway: monolithic silicon substrates, 30 mm thickness, and UV contact lithography for the patterning. These choices drive some of the other GMTNIRS design decisions.

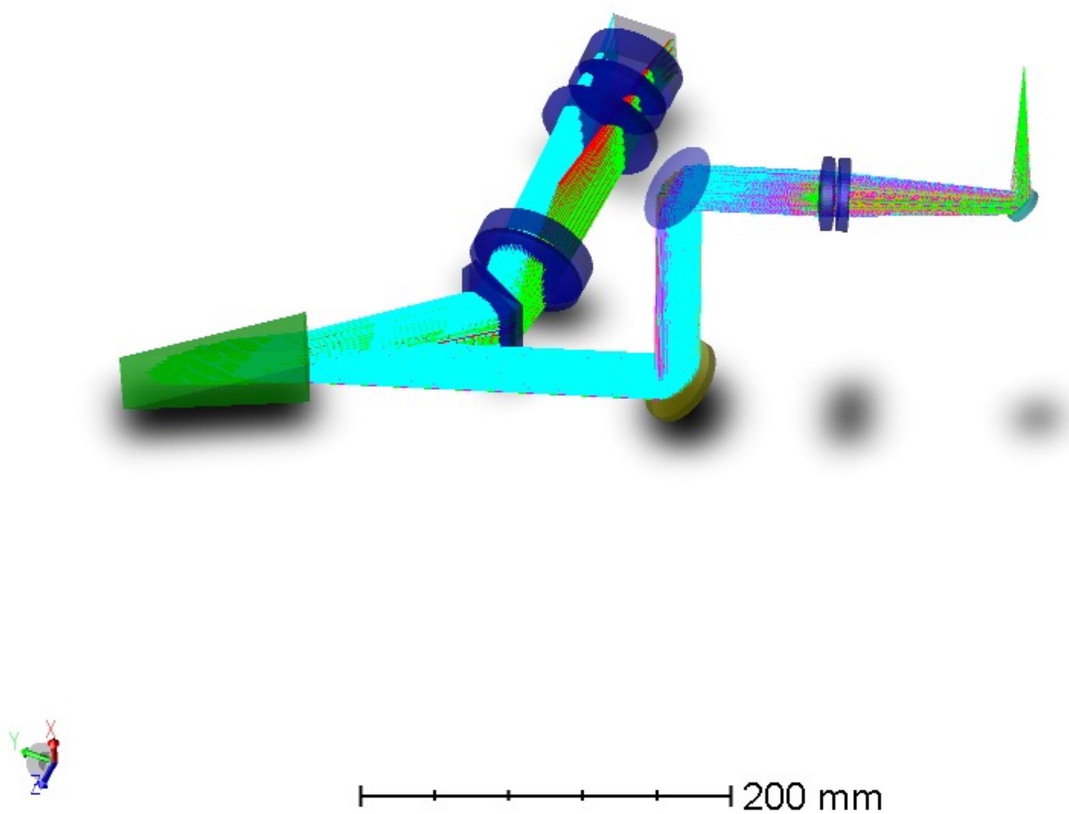

Figure 3. GMTNIRS J-band unit spectrograph. All channels receive light through a common slit (upper right). The initial fold mirror is a dichroic separating the J, H, and K channels from the L and M channels. A common collimator then sends light to additional dichroics that separate the J, H, and K band light. J-band light enters and exits the immersion grating through the flat front face and then passes directly to a VPH cross-disperser before being imaged by a three-element refractive camera onto a 2Kx2K detector.

4. CROSS-DISPERSERS

In the J, H, and K windows the availability of high-efficiency volume phase holographic gratings with adequately broad blaze functions[29] makes these devices an attractive choice for cross dispersers in an instrument like GMTNIRS where the positions are fixed but the total fractional wavelength coverage of each internal spectrograph is modest. IGRINS uses H and K band cross dispersers in a white pupil layout. The analysis for GMTNIRS reported at the Montreal SPIE[2] showed that we could achieve good optical performance from a design where the dispersed light went directly from the immersion grating echelle to the VPH cross disperser and then to the camera. Abandonment of the white pupil then eliminates at least two reflections from the unit spectrographs and makes them more compact. Figure 3 shows the layout of the J-band channel of GMTNIRS to illustrate the scale of the unit spectrographs with this design.

The VPH solution is not available for the L and M band because the material in which the gratings are written does not transmit well beyond 2.8 μm.[29] The 2014 design, in addition to its larger collimated beamsize at L and M, called for white pupil spectrographs for both the L and M bands with surface-relief cross-dispersers operating in first order.[2] A reduced-sized version of this design is still an option. Another possibility under investigation is the use of silicon grisms as transmissive cross-dispersers for L and M. This possibility is enabled by the good performance of the grisms the UT group has produced for JWST[30, 31] and by the further efficiency improvements implicit in the smaller etch-stop dam sizes that we can now achieve with electron-beam lithography and the chromium liftoff process.[26] With Si grism cross-dispersers, the layout of the L and M channels would strongly resemble that of the J, H, and K spectrographs and the L and M units would be similar in size to those at shorter wavelengths.

5. THE NEXT STEPS

The GMTNIRS design is evolving but beginning to take a more concrete shape. Two immersion grating surfaces have already been fabricated. The immersion grating production program will be completed over the next 12-18 months and the resulting echelle grating specifications will significantly constrain the design going forward. Even before we move into the formal preliminary design phase in early 2018, we will need to begin to carry out tasks associated with the preliminary design. We will need to revise the instrument optical layout for the new gratings and the slit-viewing camera. The new optical layout will produce a new estimate of the instrument volume and cooling requirements. As we move through this intermediate phase, we will need to be testing the revised design against the GMTNIRS science case. As the grating production ends and we retire the highest technical risk, we will begin our official preliminary design phase. We look forward to making GMTNIRS available on the Giant Magellan Telescope soon after the facility adaptive optics system becomes available. The completed instrument, mounted on GMT, will represent an enormous step forward in the capabilities for high-resolution spectroscopy in the infrared.

The work described in this paper was supported by a contract awarded to the Department of Astronomy at the University of Texas at Austin by the Giant Magellan Telescope Observatory.

REFERENCES

[1] Jacoby, G.H., “Instrumentation progress at the Giant Magellan Telescope,” in [Ground-based and Airborne Telescopes VI], Proc. SPIE, 9908-68 (June 2016)

[2] Jaffe, D.T., Barnes, S., Brooks, C., Gully-Santiago, M., Pak, S., Wang, W., and Yuk, I., “GMTNIRS (Giant Magellan Telescope Near-Infrared Spectrograph): optimizing the design for maximum science productivity and minimum risk,” 2014, Proc. SPIE, 9147, E22J

[3] Lee, S., Yuk, I., Lee, H., Wang, W., Park, C., Park, K., Chun, M., Pak, S., Strubhar, J., Deen, C., Gully-Santiago, M., Rand, J., Seo, H., Kwon, J., Oh, H., Barnes, S., Lacy, J., Goertz, J., Park, W., Pyo, T., Jaffe, D.T., “GMTNIRS (Giant Magellan Telescope near-infrared spectrograph): design concept,” 2010, Proc. SPIE, 7735, E2KL

[4] Bowler, B., Liu, M., Dupuy, T., and Cushing, M., “Near-infrared Spectroscopy of the Extrasolar Planet HR 8799 b,” 2010, ApJ, 723, 850

[5] Oppenheimer, B., Baranec, C., Beichman, C., Brenner, D., Burruss, R., Cady, E., Crepp, J. R., Dekany, R., Fergus, R., Hale, D., Hillenbrand, L., Hinkley, S., Hogg, D., King, D., Ligon, E., Lockhart, T., Nilsson, R., Parry, I. R., Pueyo, L., Rice, E., Roberts, J. E., Roberts, L.C., Shao, M., Sivaramakrishnan, A., Soummer, R., Truong, T., Vasisht, G., Veicht, A., Vescelus, F., Wallace, J. K., Zhai, C., Zimmerman, N., “Reconnaissance of the HR 8799 Exosolar System. I. Near-infrared Spectroscopy,” 2013, ApJ, 768, 24

[6] Ingraham, P., Marley, M., Saumon, D., Marois, C., Macintosh, B., Barman, T., Bauman, B., Burrows, A., Chilcote, J., De Rosa, R., Dillon, D., Doyon, R., Dunn, J., Erikson, D., Fitzgerald, M., Gavel, D., Goodsell, S.,

Graham, J., Hartung, M., Hibon, P., Kalas, P., Konopacky, Q., Larkin, J. Maire, J., Marchis, F., McBride, J., Millar-Blanchaer, M., Morzinski, K., Norton, A., Oppenheimer, R., Palmer, D., Patience, J., Perrin, M., Poyneer, L., Pueyo, L., Rantakyrö, F., Sadakuni, N., Saddlemyer, L., Savransky, D., Soummer, R., Sivaramakrishnan, A., Song, I., Thomas, S., Wallace, J., Wiktorowicz, S., Wolff, S., "Gemini Planet Imager Spectroscopy of the HR 8799 Planets c and d," 2014, ApJL, 794, L15

[7] Zurlo, A., Vigan, A., Galicher, R., Maire, A., Mesa, D., Gratton, R., Chauvin, G., Kasper, M., Moutou, C., Bonnefoy, M., Desidera, S., Abe, L., Apai, D., Baruffolo, A., Baudoz, P., Baudrand, J., Beuzit, J., Blancard, P., Boc caletti, A., Cantalloube, F., Carle, M., Cascone, E., Charton, J., Claudi, R. U., Costille, A., de Caprio, V., Dohlen, K., Dominik, C., Fantinel, D., Feautrier, P., Feldt, M., Fusco, T., Gigan, P., Girard, J. H., Gisler, D., Gluck, L., Gry, C., Henning, T., Hugot, E., Janson, M., Jaquet, M., Lagrange, A., Langlois, M., Llored, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Mawet, D., Meyer, M. R., Milli, J., Moeller-Nilsson, O., Mouillet, D., Origné, A., Pavlov, A., Petit, C., Puget, P., Quanz, S. P., Rabou, P., Ramos, J., Rousset, G., Roux, A., Salasnich, B., Salter, G., Sauvage, J., Schmid, H. M., Soenke, C., Stadler, E., Suarez, M., Turatto, M., Udry, S., Vakili, F., Wahhaj, Z., Wildi, F., and Antichi, J., "First light of the VLT planet finder SPHERE. III. New spectrophotometry and astrometry of the HR 8799 exoplanetary system," 2016, A&A, 587, A57

[8] Brogi, M., de Kok, R. J., Albrecht, S., Snellen, I.A.G., Birkby, J. L., and Schwarz, H., "Rotation and Winds of Exoplanet HD 189733 b Measured with High-dispersion Transmission Spectroscopy," 2016, ApJ, 817, 106

[9] Schwarz, H., Brogi, M., de Kok, R., Birkby, J., and Snellen, I., "Evidence against a strong thermal inversion in HD 209458b from high-dispersion spectroscopy," 2015, A&A, 576, A111

[10] Birkby, J. L., de Kok, R. J., Brogi, M., de Mooij, E. J. W., Schwarz, H., Albrecht, S., and Snellen, I.A.G., "Detection of water absorption in the day side atmosphere of HD 189733 b using ground-based high-resolution spectroscopy at 3.2 μm," 2013, MNRAS, 436, L35

[11] Lockwood, A., Johnson, J., Bender, C., Carr, J., Barman, T., Richert, A., and Blake, G., "Near-IR Direct Detection of Water Vapor in Tau Boötis b," 2014, ApJL, 783, L29

[12] Brogi, M., de Kok, R.J., Birkby, J.L., Schwarz, H., and Snellen, I.A.G., "Carbon monoxide and water vapor in the atmosphere of the non-transiting exoplanet HD 179949 b," 2014, A&A, 565, A124

[13] Snellen, I., de Kok, R., Birkby, J. L., Brandl, B., Brogi, M., Keller, C., Kenworthy, M., Schwarz, H., and Stuik, R., "Combining high-dispersion spectroscopy with high contrast imaging: Probing rocky planets around our nearest neighbors," 2015, A&A, 576, A59

[14] 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).

[15] 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).

[16] Mace, G.N., "300 nights of science with IGRINS at McDonald Observatory," in [Ground-based and Airborne Telescopes VI], Proc. SPIE, 9908-11 (June 2016)

[17] Quirrenbach, A., Amado, P., Caballero, J., Mundt, R., Reiners, A., Ribas, I., Seifert, W., Abril, M., Aceituno, J., Alonso-Floriano, F., Ammler-von Eiff, M., Antona Jiménez, R., Anwand-Heerwart, H., Azzaro, M., Bauer, F., Barrado, D., Becerril, S., Béjar, V.J.S., Benítez, D., Berdiñas, Z. M., Cárdenas, M., Casal, E., Claret, A., Colomé, J., Cortés-Contreras, M., Czesla, S., Doellinger, M., Dreizler, S., Feiz, C., Fernández, M., Galadí, D., Gálvez-Ortiz, M., García-Piquer, A., García-Vargas, M., Garrido, R., Gesa, L., Gómez Galera, V., González Álvarez, E., González Hernández, J. I., Grözinger, U., Guàrdia, J., Guenther, E. W., de Guindos, E., Gutiérrez-Soto, J., Hagen, H.-J., Hatzes, A. P., Hauschildt, P. H., Helmling, J., Henning, T., Hermann, D., Hernández Castaño, L., Herrero, E., Hidalgo, D., Holgado, G., Huber, A., Huber, K. F., Jeffers, S., Joergens, V., de Juan, E., Kehr, M., Klein, R., Kürster, M., Lamert, A., Lalitha, S., Laun, W., Lemke, U., Lenzen, R., López del Fresno, Mauro, López Martí, B., López-Santiago, J., Mall, U., Mandel, H., Martín, E. L., Martín-Ruiz, S., Martínez-Rodríguez, H., Marvin, C. J., Mathar, R. J., Mirabet, E., Montes, D., Morales Muñoz, R., Moya, A., Naranjo, V., Ofir, A.,

Oreiro, R., Pallé, E., Panduro, J., Passegger, V.-M., Pérez-Calpena, A., Pérez Medialdea, D., Perger, M., Pluto, M., Ramón, A., Rebolo, R., Redondo, P., Reffert, S., Reinhardt, S., Rhode, P., Rix, H.-W., Rodler, F., Rodríguez, E., Rodríguez-López, C., Rodríguez-Pérez, E., Rohloff, R.-R., Rosich, A., Sánchez-Blanco, E., Sánchez Carrasco, M. A., Sanz-Forcada, J., Sarmiento, L. F., Schäfer, S., Schiller, J., Schmidt, C., Schmitt, J. H. M. M., Solano, E., Stahl, O., Storz, C., Stürmer, J., Suárez, J. C., Ulbrich, R. G., Veredas, G., Wagner, K., Winkler, J., Zapatero Osorio, M. R., Zechmeister, M., Abellán de Paco, F. J., Anglada-Escudé, G., del Burgo, C., Klutsch, A., Lizon, J. L., López-Morales, M., Morales, J. C., Perryman, M. A. C., Tulloch, S. M. and Xu, W., "CARMENES instrument overview," 2014, Proc. SPIE, 9147, 91471F

[18] Ge, J., Zhao, B., Powell, S., Jiang, P., Uzakbaiuly, B. and Tanner, D., "An infrared high resolution silicon immersion grating spectrometer for airborne and space missions," 2014, Proc. SPIE, 9143, 91434T

[19]Mahadevan, S., Ramsey, L., Terrien, R., Halverson, S., Roy, A., Hearty, F., Levi, E., Stefansson, G., Robertson, P., Bender, C., Schwab, C. and Nelson, M., "The Habitable-zone Planet Finder: A status update on the development of a stabilized fiber-fed near-infrared spectrograph for the for the Hobby-Eberly telescope," 2014, Proc. SPIE, 9147, 91471G

[20]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," 2014, Proc. SPIE, 9147, 91471E

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

[22] Afsar, 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).

[23] Agócs ,T., "Optical tests of the Si immersed grating demonstrator for METIS," in [Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation], Proc. SPIE, 9912-41 (June 2016)

[24] Gully-Santiago, M., Jaffe, D.T., and White, V., "Optical characterization of gaps in directly bonded Si compound optics using infrared spectroscopy," 2015, Applied Optics, 54, 10177

[25] Gully-Santiago, M., Jaffe, D.T., Brooks, C., Wilson, D., and Muller, R., "High performance Si immersion gratings patterned with electron beam lithography," 2014, Proc. SPIE, 9151, 91515K

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

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

[28] 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).

[29] Arns, J., "Performance characteristics of advanced volume phase holographic gratings for operation in the near infrared," in [Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation], Proc. SPIE, 9912 (Sept. 2016).

[30] Jaffe, D.T., Wang, W., Marsh, J. P., Deen, C., Kelly, D. and Greene, T., "Fabrication and test of silicon grisms for JWST-NIRCam," 2008, Proc. SPIE, 7010, 70103L

[31] Mar, D.J., Marsh, J.P., Jaffe, D.T., Keller, L.D., and Ennico, K.A., "Performance of large chemically etched silicon grisms for infrared spectroscopy," 2006, Proc. SPIE, 6269, 62695R