OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** engineering⋆

Wide Integral Field Infrared Spectrograph Commissioning and First-Light Science Programs

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Abstract of Scientific Justification

We propose the commissioning of the Wide Integral Field Infrared Spectrograph (WIFIS) and its first-light science observations on the Bok telescope. (*Note that the WIFIS commissioning was proposed in the previous semester on a shared-risk basis, but the delay in the instrument development has postponed the commissioning to this semester.*) WIFIS is an image slicer-based near-infrared (NIR; 0.9–1.8 μm) integral field spectrograph of $\sim 50'' \times 20''$ integral field size. It has zJ and H band spectral coverage with $R \simeq$ 3,000 (zJ) and 2,200 (H) spectral resolving power. Because of its unprecedentedly large integral field size in the NIR, WIFIS is expected to provide highly competitive, unique data for studying dynamics and chemistry of extended objects in the Milky Way and galaxies, ranging from observations of supernova remnants and star-forming regions to nearby galaxies and mergers. For the WIFIS commissioning and first-light observations that we propose here, we request "up to" 26 bright nights of the Bok telescope in May-July (2015) distributed into 3 categories: (1) instrument commissioning engineering (5 nights), (2) high-priority science programs (10 nights), and (3) medium-priority science programs (11 nights). The proposed WIFIS first-light science programs are five-fold: supernova nucleosynthesis and explosion mechanisms by observing young supernova remnants; spectroscopic follow-up observations of newly-discovered massive stellar clusters; initial mass functions of nearby ellipticals and bulges; massive star formation in nearby galaxies; and galaxy merging processes at z = 0.4–0.6. The proposed programs should not only test and demonstrate the capabilities of WIFIS but also produce quick scientific results and set the stage for future observing programs.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	90"	f/9	WIFIS	*		15–26	bright	May-July	May-July	no	no

Scheduling constraints and unusable dates *(up to 4 lines)***:** The proposed programs are in principle on a shared-risk basis. There is a chance that the instrument may not be ready by May 2015 for observations, although we feel the possibility for that to happen is small. While we request 15 nights at high priority, we have requested additional time for science programs in the event that there is additional time available.

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A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Several Standard Stars			
2	Cassiopeia A	23:23:26	+58:48:00	Young Supernova Remnant
3	G11.2–0.3	18:11:30	–19:25:00	Young Supernova Remnant
4	G24-SFC8	18:36:40	–07:58:47	Massive Stellar Cluster
5	G24-SFC10	18:36:25	–06:55:38	Massive Stellar Cluster
6	G24-SFC12	18:38:17	–06:06:44	Massive Stellar Cluster
7	G37-SFC22	19:01:08	+03:27:27	Massive Stellar Cluster
8	NGC 6125	16:19:12	+57:59:03	E1 Galaxy, $z = 0.015$, J_{tot} = 10.1
9	NGC 6146	16:25:10	+40:53:34	E5 Galaxy, $z = 0.029$, J_{tot} = 10.5
10	NGC 6411	17:35:33	+60:48:48	E4 Galaxy, $z = 0.012$, J_{tot} = 10.0
11	NGC 6081	16:12:57	+09:52:02	S0a Galaxy, $z = 0.017$, J_{tot} = 10.7
12	NGC 6154	16:25:31	+49:50:25	Sab Galaxy, $z = 0.020$, J_{tot} = 11.1
13	NGC 7436B	22:57:58	+26:09:00	E2 Galaxy, $z = 0.025$, J_{tot} = 10.1
14	NGC 7194	22:03:31	+12:38:12	E3 Galaxy, $z = 0.027$, J_{tot} = 10.7
15	M82	09:55:53	+69:40:49	Massive Star-forming Region
16	N3351	10:43:58	+11:42:13	Massive Star-forming Region
17	N5194	13:30:03	+47:09:50	Massive Star-forming Region
18	D2064953	10:00:43	+01:52:05	Galaxy merger, $z \simeq$ 0.50, z = 18.4
19	D2090671	09:59:22	+01:55:45	Galaxy merger, $z \simeq$ 0.43, z = 18.5
20	D2078436	10:01:10	+01:54:05	Galaxy merger, $z \simeq$ 0.52, z = 18.6
21	D2006455	09:59:16	+01:43:12	Galaxy merger, $z \simeq$ 0.53, z = 18.6
22	D2235227	10:00:02	+02:16:30	Galaxy merger, $z \simeq$ 0.51, z = 18.9
23	D1069539	02:25:11	–04:50:33	Galaxy merger, $z \simeq$ 0.43, z = 17.2
24	D1272051	02:27:32	–04:23:30	Galaxy merger, $z \simeq$ 0.41, z = 17.3
25	D1061787	02:24:27	–04:51:58	Galaxy merger, $z \simeq$ 0.52, z = 18.3
26	D1226069	02:24:47	–04:29:45	Galaxy merger, $z \simeq$ 0.54, z = 18.8

Approval for Instrument Use from PI: The PI of the proposal is the PI of the instrument (WIFIS).

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

The Wide Integral Field Infrared Spectrograph (WIFIS) is a near-infrared (NIR) integral field spectrograph that has an unprecedentedly large integral field size of $\sim 50'' \times 20''$ with a $\sim 1''$ spatial resolution when coupled with the Bok 90" telescope (Sivanandam et al. 2012). It has been developed at the University of Toronto (P.I. Dae-Sik Moon) in collaboration with the University of Florida, Korea Astronomy and Space Science Institute and the University of Arizona. Its expected sensitivity and development progress are available at: *http://thor.dunlap.utoronto.ca/∼suresh/main/?page_id=14*, and Figure 1 shows its fully assembled model. WIFIS is optimized for high sensitivity, modest spectral resolution ($R \simeq$ 3,000) observations in the zJ (0.9–1.35 μm) band, whereas it offers $R \simeq$ 2,200 in H-band with a reduced sensitivity due to thermal background. The unique combination of the large integral field size, wavelength coverage, and spectral resolving power of WIFIS opens up entirely new scientific areas of research for investigating dynamics and chemistry of extended objects in the NIR regime. It is especially well-equipped to follow-up targets observed by wide-field, optical, integral-field spectroscopic surveys (e.g., MaNGA) just becoming prevalent.

The full assembly of WIFIS is currently expected to take place in 2014 December, several months behind the original schedule given in our previous proposal. The delay has been mainly caused by slow progress in mechanical designs which have been carried out by a mechanical engineer at Cornell University. The engineer has ample experiences with successfully developing several infrared astronomical spectrographs, but has had only a limited amount of time to devote to the WIFIS project, so the delays. However, most of the mechanical designs have been finished now and their fabrication is underway, while we have tested all the optical components and the detector system. Therefore, we believe that it is reasonable to consider commissioning of WIFIS in May 2015, which should give us enough time for characterization, trouble shootings and shipping. Given the situation, we propose WIFIS commissioning and first-light science observations composed of 3 categories using bright nights of the Bok telescope in May–July 2015. The first-light WIFIS science programs comprise 5 (2 Galactic; 3 extragalactic) programs – see below. In order to accommodate both the uncertainty in the instrument commissioning and rapid use of WIFIS for science programs, we propose up to 26 nights of the telescope time distributed to the following 3 categories: **(1) 5 nights for WIFIS commissioning engineering run; (2) 10 nights for high-priority science programs; (3) 11 nights for medium-priority science programs**. We request 15 nights of (1) and (2) as basic requirement, while 11 nights of (3) as supplementary if additional time is available. Below we describe the 5 first-light WIFIS science programs and the targets in the high- and medium-priority programs.

■ **Young Supernova Remnants**: Young supernova remnants (SNRs) are rich with NIR lines diagnostic of supernova nucleosynthetic processes and explosions. This is especially true for the zJ band that has transitions of Fe, S, P, O, C, and He, which have crucial information for the supernova nucleosyntheses and explosion mechanisms. We propose to conduct zJ- and H-band WIFIS observations of the two historic young core-collapse SNR Cassiopeia A (Cas A; Fig. 1[b]) and G11.2–0.3. We will first calculate the extinction using the line ratios of [Fe II] 1.644 and 1.257 μm transitions originating from the same upper level, which will make it possible to conduct precise abundance comparisons of the supernova nucleosynthetic elements. For instance, we have recently discovered increased abundance of P in Cas A (Koo et al. 2013), confirming the *in situ* creation of P – one of the 6 indispensable elements of human bodies. The proposed WIFIS observations will provide a comprehensive view of the distribution of the nucleosynthetic elements and information for their abundance and kinematics in the two young SNRs.

■ **New Massive Young Stellar Clusters**: The competitive multiplexing capability of WIFIS (i.e., $\sim$ 500 spaxels) is well-suited to follow-up spectroscopic observations of new massive ($\gtrsim 10^4 M_\odot$) young stellar clusters identified in recent 2MASS color-selection analyses of the Galactic plane (e.g., Rahman et al. 2013). Each of these new massive clusters, which are associated with nearby giant H II regions, is expected to harbor more than 100 previously-unknown OB stars. They may occupy an important portion of the cluster mass function in the Galaxy, and NIR spectroscopic follow-up observations is imperative for understanding their nature and reliable characterization of their properties. Multiple exposures of WIFIS toward the central parts of these clusters will quickly reveal the spectral types and luminosity classes of the stars therein. Most of the OB stars will be identifiable in H I and He I absorption lines in the WIFIS band, whereas supergiants and more evolved stars of strong stellar winds will show broad emission lines in H I transitions.

■ **Initial Mass Functions in Bulges and Ellipticals**: The goal of this program is to use NIR absorption line diagnostics to study the initial mass function (IMF) of nearby bulges of spirals and ellipticals. The NIR offers a unique window for constraining the dwarf-to-giant ratio in galactic spectra because it contains numerous stellar absorption features (e.g., Na I, CN, FeH Wing-Ford) that are sensitive to either dwarfs or giants. There has been recent optical work by Conroy et al. (2012, 2013) that suggests that the IMF becomes increasingly bottom-heavy as the velocity dispersion (i.e., mass) of the bulge increases. The most massive ellipticals exhibit an IMF that is much more bottom-heavy than Salpeter. This is quite surprising and controversial, and there is concern that the line diagnostics used in these works are affected by incomplete metallicity coverage of the spectrophotometric stellar data used in the population synthesis models. We have selected 8 galaxies from the CALIFA sample for WIFIS follow-up with morphological types ranging from E to Sb. WIFIS observations of the dwarf/giant specific absorption features, combined with optical diagnostics obtained from the public CALIFA data, can constrain the giant/dwarf ratio, and hence the low-end IMF. This, in turn, relates to the baryonic and dark matter distributions in these galaxies when kinematics are included. The program will be a precursor to a future larger WIFIS survey of CALIFA/MaNGA galaxies.

■ **Massive Star Formation in Nearby Galaxies**: With the aid of NIR emission line diagnostics and continuum emission available from WIFIS observations, this program aims to study the nature of massive star formation by observing nearby star forming galaxies. Using He I, [Fe II], Paβ, and infrared continuum in the zJ band as diagnostics, this study will be able to date young star clusters in nearby galaxies by constraining the OB stellar fraction in active star-forming regions. WIFIS observations will also be able to address the longstanding puzzle of the preferred locations for massive star formation – do they form in clusters or in the field? Additionally, comparison between the supernova rate and star forming rate, which can be traced by [Fe II] and Paβ lines, respectively (e.g., Rosenberg et al. 2012), may allow a spatial and temporal mapping of formation versus death of massive stars in nearby galaxies (e.g., Boker et al. 2008).

■ **Galaxy Mergers at $z \simeq$ 0.4–0.6**: Galaxy mergers play a central role in the evolution of galaxies, especially the formation of massive galaxies (Hopkins et al. 2006). In order to extend our understanding of merging processes beyond the local Universe, we propose to conduct WIFIS zJ-band observations of 10 merging galaxies with stellar masses of $\sim 10^{10}$–$10^{11} M_\odot$ in the redshift range $z \simeq$ 0.4–0.6. (Note that "Target list" contains information for only part of the 10 mergers due to the limit in the total number of objects.) These mergers are close pairs which are morphologically classified to be in different stages of their merging process from the CFHT Legacy Survey fields (Chou et al. 2011). We will first trace the star forming properties and the gas kinematics of these mergers using the spatial distribution and velocity structure of the redshifted Hα emission, and then determine their merging stages and the level of induced star formation along with the mass assembly process from the interactions. This will enable us to compare merging processes between the local Universe and $z \simeq$ 0.4–0.6, and may serve as a stepping stone for more comprehensive study of merger history in the future.

[Science Program Priority]: **[1]** High-priority Programs (10 nights in total): The targets for our high-priority science programs consist of Cas A (3 nights), two massive stellar clusters (1 night), four galaxies for the IMF study (3 nights), M82 for massive star formation in nearby galaxies (1 night), and four merging galaxies (2 nights). (See the next page for time justification.) This combination of the targets of high priority will enable us to start the proposed WIFIS science programs in a rapid manner. **[2]** Medium-priority Programs (11 nights in total): The targets for the medium-priority science programs consist of the young SNR G11.2–0.3 (3 nights), two additional massive stellar clusters (1 nights), four galaxies for the IMF study (3 nights), two other galaxies for the massive star formation study (1 night), and six merging galaxies (3 nights). This combination of the targets of medium priority will deepen our understanding of the proposed science programs.

REFERENCES

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Chou, R. C. Y., et al. 2011, AJ, 141, 87
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Rosenberg, M. J. F., et al. 2012, A&A, 540, 116
Sivanandam, S., et al. 2012, SPIE, 8446, 84464S
Rahman, M., et al. 2013, ApJ, 766, 135

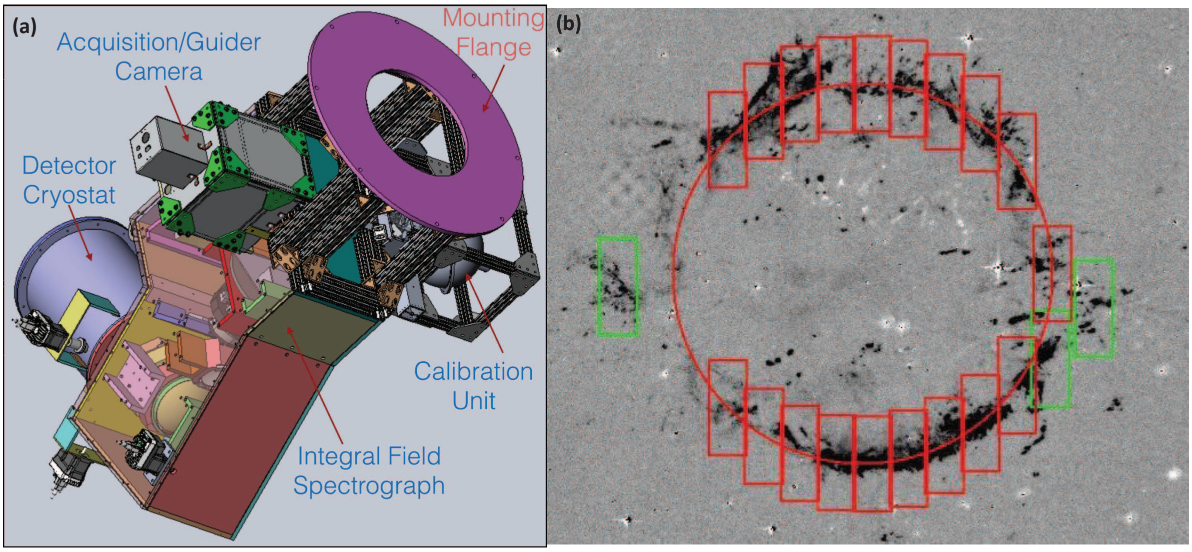

Figure 1: (a) Fully assembled model of WIFIS where several major components of the instrument are highlited with arrows. The top cover of Integral Field Spectrograph has been made transparent to reveal the optics inside. (b) Distribution of the [Fe II] 1.644 μm emission of Cas A (Koo et al. 2013). The rectangular boxes represent the $50'' \times 20''$ integral field size of WIFIS. The diameter of the [Fe II] shell is $\sim 4'$.

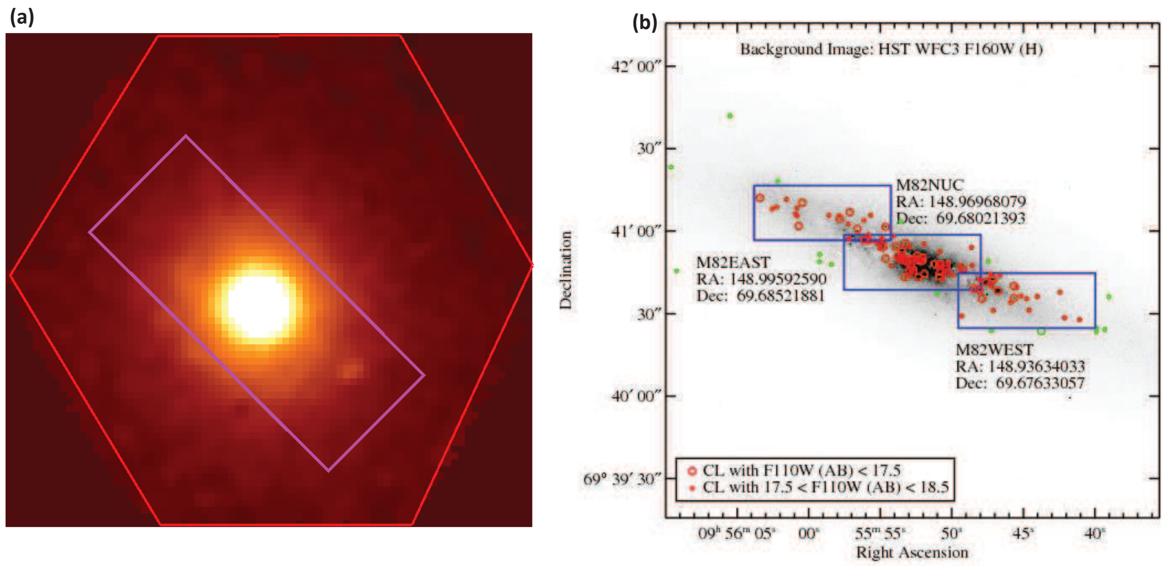

Figure 2: (a) Optical continuum image of NGC 1349 (S0 galaxy) constructed from a CALIFA spectral cube. The CALIFA and WIFIS fields-of-view are shown by the red and magenta regions, respectively. The WIFIS field has substantial overlap with the CALIFA field and has comparable spatial resolution. (b) Three WIFIS fields of M82 overlaid with the locations of known massive star clusters in the galaxy.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Instrument Readiness: As we briefly described in "Scientific Justification," the delay in the instrument can been mostly attributed to the slowness of the detailed mechanical design phase. The mechanical design of the instrument is now undergoing final checks and the fabrication and testing of individual mechanical sub-components have begun. We have all of the optical components of the integral spectrograph in hand and have already tested the detector electronics. All of the hardware for the calibration unit and the guider/acquisition camera are also in hand and are undergoing tests. The final stage of instrument assembly will take place during the end of this year and at the latest in January 2015. After integration, we have allotted three months to carry out thorough testing of instrument performance and rectify any issues that may arise.

Commissioning Engineering: During the commissioning nights, we plan to carry out numerous tests to characterize the WIIFS performance on the Bok telescope and also to ensure that it is functioning to its best possible level based on the results of performance characterization. These include field alignment and plate scale calibration, sensitivity measurements, stability characterization, and various types of software tests. We anticipate this will take approximately 5 nights of work including contingencies.

Supernova Remnants: As in Fig. 1(b), we need $\sim$ 20 separate WIFIS pointings to cover the entire [Fe II] shell of Cas A, whereas we need half of that for G11.2–0.3 due to its smaller size. The typical [Fe II] 1.257 μm line intensity within $1'' \times 1''$ of the Cas A shell is $\sim 4 \times 10^{-15}$ erg cm^{-2} s^{-1} (Koo et al. 2013). This will provide high ($\gtrsim$ 10) S/N ratio spectra of most of the expected transitions from the supernova nucleosynthetic elements (e.g., S, P, Fe, He) in the zJ band with 50-min exposure time per pointing. In addition, we also plan to conduct short 10-min observations in H-band to estimate the brightness of the [Fe II] 1.644 μm transition for the extinction measurement. Therefore, we request 3 nights of the observing time for Cas A in addition to 3 nights for observations of G11.2–0.3 which is smaller but fainter than Cas A.

Massive Stellar Clusters: According to Rahman et al. (2013), the newly-identified massive stellar clusters in 2MASS images show heavy concentration of stellar densities within the central area of $\sim 1'$, which requires four separate WIFIS exposures to observe the center of one cluster in both the zJ and H bands. One hour integration time for each exposure is expected to give enough S/N ratios required to classify the stars identified in the 2MASS images, which is approximately equivalent to observing two massive stellar clusters per night. We request in total of 2 nights for observations four massive stellar clusters – two clusters as high priority and the other two as medium priority.

IMF in Galaxies: We propose to observe eight galaxies for the IMF study. All of the eight galaxies have existing public CALIFA optical integral field spectroscopic data (Fig. 2[a]), which will enable us to compare the optical and NIR emission from their central regions that we plan to observe with WIFIS. A number of stellar absorption features in the zJ band will be used to determine the dwarf/giant ratio and hence the IMF of these galaxies, whereas the comparison between the optical (CALIFA) and NIR (WIFIS) emission is expected to provide additional constraints in fitting the stellar population synthesis models. The integrated J-band brightness of these galaxies are $J_{tot} \sim 10$, and we expect to obtain S/N ratio > 100 per spectral resolution element in $1.5'' \times 1.5''$ with 5-hr total integration time (including overhead). For all the eight galaxies, this is equivalent to 6 nights of observing time split equally between the high and medium priority.

Massive Star-formation in Nearby Galaxies: In this program of studying massive stars in galaxies, we have three galaxies to observe with five pointings: three for M82 as in Fig. 2[b] and N3351 and N5194 centered on their known young stellar clusters or giant H II regions. We need 2-hr exposure time for each pointing for M82, whereas we do 3-hr time for N3351 and N5194 which are fainter than M82. These exposures are expected to give S/N ratio $\gtrsim$ 10 spectra for the Paβ, [Fe II] and He I lines. We request 2 nights (including overhead) in total: 1 for M82 (high priority) and the other 1 for N3351 and N5194.

Galaxy Mergers: We propose to observe up to 10 bright merging galaxies from which we expect to detect their redshifted Hα emission of S/N ratio $\gtrsim$ 10 with 4-hr exposure in the zJ band for each source. This is equivalent to 5 nights in total: 2 nights for high priority and 3 nights for medium priority.

$\boxed{\textbf{Summary of Time Requested and Awarded}}$ *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Once successfully commissioned on the Bok telescope with an acceptable performance, we expect WIFIS to be available to researchers at the University of Arizona and the University of Toronto in a collaborative manner for a few years. The details of the governing principles of the WIFIS operation on the Bok telescope have been discussed and will be finalized in coming months. We anticipate WIFIS to be heavily subscribed for the bright time of the Bok telescope.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

We were awarded several nights in 2014 for WIFIS commissioning and first-light science programs, quite similar to what is proposed this time. Because of the delay in the instrument development, however, we informed that TAC in advance that we were unable to use the allocated time. Other than that, the PI (Dae-Sik Moon) has had no previous observing time associated with Steward Observatory facilities. The UA co-I's have had a number of programs using Steward Observatory facilities, but none related to the WIFIS instrument that we propose to use here.