OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term*

Wide Integral Field Infrared Spectrograph Eearly Science Programs

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Abstract of Scientific Justification

We propose to conduct early science programs of the Wide Integral Field Infrared Spectrograph (WIFIS) that are expected to be commissioned on the Bok telescope in 2015 summer. 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 capable of providing 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. The proposed WIFIS early science programs are five-fold: supernova nucleosynthesis and explosion mechanisms by observing young supernova remnants; accretion and outflows of young stellar objects in 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. We expect the large two dimensional spectroscopic data from WIFIS to shed new important insights into our understanding of these objects.

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	*		25	bright	Sep–Dec	Sep–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)***:** The proposed programs are in principle on a shared-risk basis since the instrument (WIFIS) yet to be commissioned and its sensitivity is unknown. While we request 25 bright nights, the request is flexible. We will be able to use less or more observing time in an effective manner since we have multiple programs of multiple objects to observe.

no text past this line

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	Crab Nebula	05:34:32	+22:00:52	Young Supernova Remnant
4	Orion Nebular Cluster	05:34:48	–05:23:24	Young Stellar Objects, J=10–15
5	NGC 0776	01:59:56	+23:38:39	SBb Galaxy, $z = 0.016$, $J_{tot} = 10.7$
6	NGC 1349	03:31:28	+04:22:51	S0 Galaxy, $z = 0.022$, $J_{tot} = 10.8$
7	NGC 7025	21:07:47	+16:20:09	Sa Galaxy, $z = 0.017$, $J_{tot} = 9.6$
8	NGC 7194	22:03:31	+12:38:12	E Galaxy, $z = 0.027$, $J_{tot} = 10.7$
9	UGC 11958	22:14:47	+13:50:24	S0a Galaxy, $z = 0.026$
10	UGC 12127	22:38:30	+35:19:41	E Galaxy, $z = 0.027$, $J_{tot} = 10.6$
11	NGC 7436B	22:57:58	+26:09:00	E Galaxy, $z = 0.025$, $J_{tot} = 10.1$
12	NGC 7563	23:15:56	+13:11:46	SBa Galaxy, $z = 0.014$, $J_{tot} = 10.4$
13	M82	09:55:53	+69:40:49	Massive Star-forming Region
14	N595	01:33:34	+30:41:36	Giant H II Regions, Young Stellar Clusters
15	N604	01:34:34	+30:47:02	Giant H II Regions, Young Stellar Clusters
16	N628	01:36:39	+15:44:21	Star Forming Region
17	N925	02:27:22	+33:33:35	Star Forming Region
18	IC101	00:20:27	+59:17:35	Young Stellar Clusters, H II Regions
19	D1069539	02:25:11	–04:50:33	Galaxy merger, $z \simeq 0.43$, z = 17.2
20	D1226069	02:24:47	–04:29:45	Galaxy merger, $z \simeq 0.54$, z = 18.8
21	D1272051	02:27:32	–04:23:30	Galaxy merger, $z \simeq 0.41$, z = 17.3
22	D1061787	02:24:27	–04:51:58	Galaxy merger, $z \simeq 0.52$, z = 18.3
23	D1142749	02:24:12	–04:40:44	Galaxy merger, $z \simeq 0.49$, z = 18.4
24	D1083368	02:26:32	–04:49:05	Galaxy merger, $z \simeq 0.53$, z = 18.1
25	D1131382	02:24:43	–04:42:17	Galaxy merger, $z \simeq 0.42$, z = 18.6
26	D1420848	02:26:34	–04:05:15	Galaxy merger, $z \simeq 0.45$, z = 18.7

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 commissioning of WIFIS is currently expected to happen in June 2015. With all remaining parts are being fabricated and delivered, we will be able to start full assembly of the instrument in April 2014.)*

Below we describe five, two Galactic and three extragalactic, WIFIS early science programs that we propose to conduct in 2015B. Four of these programs (other than the one for young stellar objects – see below) are an extension of what we proposed in 2015A as WIFIS commissioning and first-light science programs. It is possible, therefore, that a small number of the targets that we propose here will be observed in 2015A during the expected WIFIS commissioning. If some targets are indeed observed in 2015A, we will replace them with new targets, and we have enough target candidates that are not included here for each of the science 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 archetypal young core-collapse SNR Cassiopeia A (Cas A; Fig. 1[b]) and the Crab Nebula. 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 six 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. We will then conduct thorough investigation into the nucleosynthesis and explosion dynamics of core-collapse supernovae. In addition, the ratio of [Fe II] to hot dust emission can trace dust destruction processes (Kokusho et al. 2013).

■ **Young Stellar Objects in Star Forming Regions**: The competitive multiplexing capability of WIFIS (i.e., $\sim$ 500 spaxels) is well-suited to the study of clustered young stellar objects (YSOs) in star forming regions, and we propose to observe $\sim 2' \times 2'$ area of the Orion Nebular Cluster with WIFIS in the zJ band. At the centre of the cluster where there is a strong aggregation of YSOs we expect to obtain spectra of several tens of YSOs simultaneously within the WIFIS integral field (= $20'' \times 50''$). Specifically, we plan to use Paβ line to trace accretion and outflow of the YSOs and [Fe II] and He I lines to help distinguish accretion and outflow components. These observations will be supplemented by time-monitoring of these lines, which will constrain the variability of accretion processes from these roughly coeval sources in a young cluster. These processes relate directly to star formation since accretion rate determines the mass growth rate of the star and to planet formation via improved understanding of disk viscosity. Because this is a time-monitoring project, it would be excellent for students (including undergraduate students), since training for a single epoch can be applied to future epochs. We would build on a previous project where we used FSPEC at the Bok telescope to monitor accretion variability (Eisner et al. 2015).

■ **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.

REFERENCES

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Rudy, R. J., et al. 1994, ApJ, 426, 646
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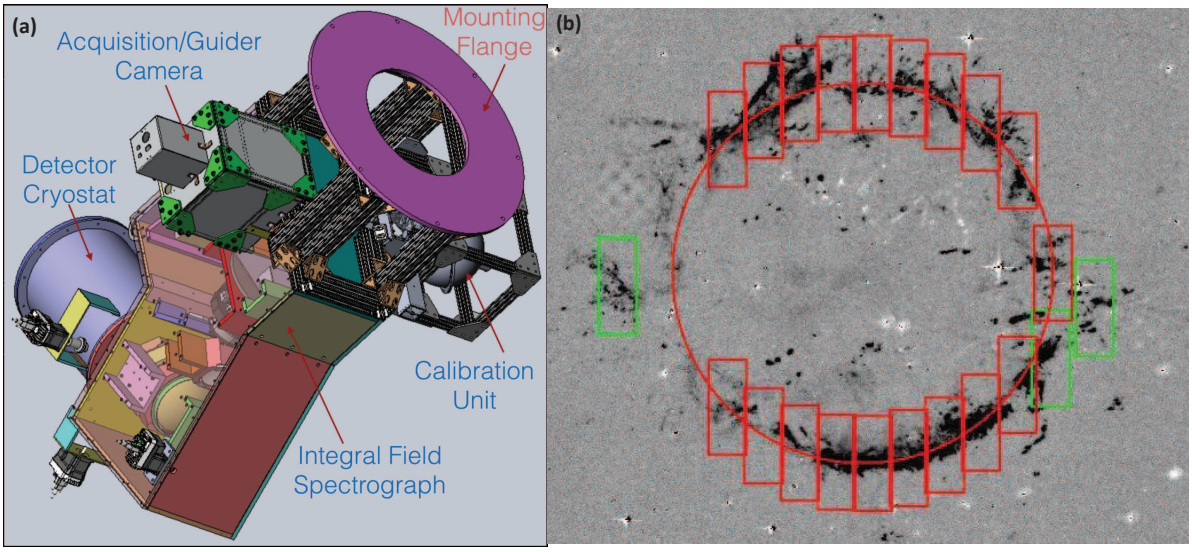

Figure 1: (a) Fully assembled model of WIFIS where several major components of the instrument are highlited with arrows. The top cover of Integral Field Spectrograph has been made transparent to reveal the optics inside. (b) Distribution of the [Fe II] 1.644 μm emission of Cas A (Koo et al. 2013). The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

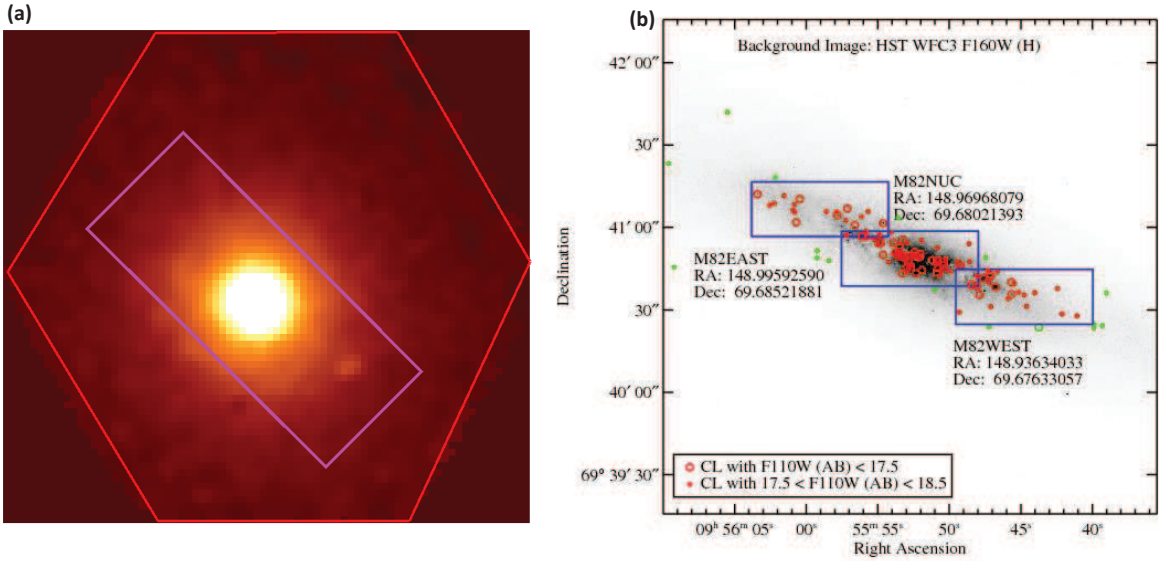

Figure 2: (a) Optical continuum image of NGC 1349 (S0 galaxy) constructed from a CALIFA spectral cube. The CALIFA and WIFIS fields-of-view are shown by the red and magenta regions, respectively. The WIFIS field has substantial overlap with the CALIFA field and has comparable spatial resolution. (b) Three 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: We will begin full integration of WIFIS in April 2015, and the expected commissioning of the instrument is June 2015. We have all of the optical components of the spectrograph in hand and have already tested the detector electronics. All the hardware components for the calibration unit and the guider/acquisition camera are also in hand and are undergoing tests. We are currently waiting for the delivery of cryostat which can happen at any moment. Once delivered, we will begin the instrument assembly. All necessary software, including both hardware control software and data reduction pipeline, are being developed.

Supernova Remnants: As in Fig. 1(b), we need ~ 20 separate WIFIS pointings to cover the entire [Fe II] shell of Cas A. 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 . The Crab Nebula, on the other hand, is $\sim 7' \times 5'$ in size filled with supernova nucleosynthetic material in a filamentary structure. In the zJ band the brightest transition is [S III] (0.9532 μm) followed by transitions of [Fe II] (1.257 μm), He I (1.083 μm) and [C I] (0.9824 and 0.9850 μm) (Rudy et al. 1994). The intensity of the [S III] line within $1'' \times 1''$ is $\sim 7 \times 10^{-15}$ erg cm^{-2} s^{-1} (or $\sim 4 \times 10^{-13}$ erg cm^{-2} s^{-1} over $9''6 \times 8''1$, see Rudy et al. 1994). With 10-min exposure for each pointing, which can provide S/N ratio > 10 spectra for the 4 bright transitions, we will be able to cover the entire Crab Nebula with WIFIS in 3 nights.

Orion Nebular Cluster: The central $\sim 2\,' \times 2'$ area of the Orion Nebular Cluster contains more than 250 YSOs of J = 10–15. The size of the area requires 16 separate WIFIS pointings, while 20-min exposure in the zJ band for each pointing will give us very high S/N ratio spectra for Paβ, [Fe II] and He I lines from the YSOs. This adds up to one full night, including overhead, for observing the YSOs in the Orion Nebular Cluster. In order to investigate their variabilities, we propose to repeat the observations four times (= four nights).

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). We request six nights for observing eight galaxies for this program.

Massive Stars in Galaxies: In this program of studying massive stars in galaxies, we have maximum 8 galaxies with 12 total pointings – M82(3) (Fig. 2[b]), IC10(2), N5194, N3351, N925, N628, N604(2) and N595 – centered on their known young stellar clusters, star forming regions or giant H II regions. (The numbers in the parentheses are the number of pointings for the galaxy. Note that not all these galaxies appear in the Target list due to the limit to the number of the allowed targets in the list.) We require 2-hr exposure time for each pointing, which is expected to give S/N ratio $\gtrsim$ 10 spectra for the Paβ, [Fe II] and He I lines. We, therefore, require four nights in total for this program, including overhead.

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 five nights in total.

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 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 the near future. 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 those 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. In the 2015A season, we have bright nights allocated between May and July for WIFIS commissioing and first-light science programs, and we plan to commission WIFIS in June 2015. Other than those, 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.