OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term*

Characterizing YSOs in the Heart of the Orion Nebula Cluster and NGC 1977 using MMT/MMIRS multi-object spectroscopy

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Abstract of Scientific Justification

Gas- and dust-rich protoplanetary disks around young stars are sites of planet formation. These disks typically dissipate on a 3-5 Myr time scale via mainly accretion of materials onto the star or via photo-evaporation. This proposed study will investigate disk dispersal due to external photoevaporation in the presence of ionizing massive stars in the immediate vicinity of the disk systems. Our samples are located at the very center of the Orion Nebula Cluster (ONC) and NGC 1977, the ideal sites to study the effects of external photoevaporation on disk dispersal. The ONC offers strong UV radiation environment, and its sibling star forming region, NGC 1977, provides a unique laboratory to study moderate UV environment, since its most massive star is a B star. A number of direct observations of photoevaporating protoplanetary disks (proplyds) were detected mostly in ONC, but we have recently discovered that there are proplyds found in NGC 1977 as well as very rich population of YSOs with jets and outflows. We propose to use the MMT/MMIRS multi-object spectrograph to obtain IR spectra ($H\&K$) for $\sim$**100** young stellar objects (YSOs) in the center of ONC, and for $\sim$80 YSOs in the center of NGC 1977. This observation is an important part of the astrobiology program, *Earths in Other Solar Systems (EOS)*, a part of NASA's Nexus for Exoplanetary System Science. We will derive stellar properties (masses & ages) and estimate accretion rates from the proposed observations. These are important for understanding the role the external photoevaporation plays on disk evolution. This program will also complement to an ALMA program (observed) to measure disk masses of YSOs in the same area we propose here (center of ONC near an O star, θ^1 Ori C). This is a resubmission of previously approved MMIRS programs.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/5	MMIRS	*		2	grey	Nov–Dec	Oct–Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*:

no text past this line

A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	*(Identify at least 1 object)*			
2	Field 1	05:35:11.87	−05:21:47.6	ONC, K=13.5–14.5, Total Exp=30 minutes
3	Field 2	05:35:11.19	−05:20:38.8	ONC, K=13.5–15.5, Total Exp=30 minutes
4	Field 3	05:35:11.19	−05:20:38.8	ONC, K=13.5–15.5, Total Exp=30 minutes
5	Field 4	05:35:11.19	−05:20:38.8	ONC, K=13.5–15.5, Total Exp=30 minutes
6	Field 4	05:35:11.19	−05:20:38.8	ONC, K=13.5–15.5, Total Exp=30 minutes
7	Field 4	05:35:11.19	−05:20:38.8	ONC, K=13.5–15.5, Total Exp=30 minutes
8	Field 5	05:35:23.140	−04:50:17.73	NGC 1977, K=12–14, Total Exp=30 minutes
9	Field 6	05:35:20.10	−04:51:34.77	NGC 1977, K=12–14, Total Exp=30 minutes
10	Field 7	05:35:25.64	−04:47:34.29	NGC 1977, K=12–14, Total Exp=30 minutes

Approval for Instrument Use from PI: yes

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

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

Scientific Justification

What is the lifetime of protoplanetary disks as a function of distance from a massive star? Do disks survive longer when they are farther away from external radiation sources? How much mass is lost via central star-driven photoevaporation? Gas- and dust-rich protoplanetary disks are the natural outcome of the star formation processes, and are the sites of planet formation. These disks disperse on a 3-5 Myr time scale (Haisch et al. 2001, Kim et al. 2005, Sicilia-Aguilar et al. 2006, Hernández et al. 2007, Fang et al. 2013, for a review, see Pascucci & Tachibana 2010). The dispersal of protoplanetary disks places the most important boundary condition on planet formation. What mechanisms are responsible for protoplanetary disk dispersal? Several disk dispersal mechanisms have been considered including viscous evolution (accretion), photoevaporation, giant planet formation, grain growth, magneto-rotational instability, and close companions (Artymowicz & Lubow 1994, Boss et al. 2002, Zsom et al. 2011, Pascucci et al. 2008, Alexander et al. 2014). However, the two main processes of clearing disks are viscous accretion and photoevaporation, even for isolated stars.

Here we focus on external photoevaporation of protoplanetary disks due to ionizing radiation from nearby O and B stars. External photoevaporation erodes protoplanetary disks outside-in via combination of EUV ($h\nu \gtrsim 13.6$ eV) and FUV (6 eV$\lesssim h\nu \lesssim$13.6 eV) photons. The time scale of photoevaporation in protoplanetary disks depends on proximity from the ionizing sources (massive stars) and assumed UV fluxes (Adams 2010). Adams (2010) showed that outer part of disks could be influenced due to external photoevaporation. Clearly external photoevaporation has a major impact on disk lifetime, as evinced by the proplyds (e.g., Felli et al. 1993; McCaughrean & ODell 1996) and the <u>tentative</u> trend of lower disk mass for objects close to massive stars (e.g. Mann et al. 2015).

We propose infrared spectroscopy of $\sim$**100** YSOs at the central part of the Orion nebula cluster (ONC) in immediate vicinity of ionizing sources, a O6 star, $\theta^1 C$ Ori, and 80 YSOs in the center of NGC 1977 where a B1 star dominates. This proposal aims to: 1) characterize stellar properties (e.g., spectral types, luminosity class); 2) derive age and mass using spectral types and stellar evolutionary models; 3) estimate accretion rates; and 4) combine our analysis with disk masses which will be obtained using ALMA data in ONC. This proposed study is intended to characterize sources in ONC for which disk masses will be measured with ALMA. Current data can only characterize about 76% of the population in the central part of ONC and without accretion rate estimates. In ONC we plan to obtain total 416 IR spectra (76% from from previous observations and 24% from this proposed program) using MMIRS to obtain complete census of YSOs with high extinction. We will map the central $1.5' \times 1.5'$ of ONC using ALMA during Cycle 3 (mapping larger regions in subsequent cycles), and expect to detect $\sim$200 objects which will be factor of about $\times$10 increase in number YSOs with disk mass estimates. This proposed observations will provide us an essential dataset with a large unbiased sample of young stellar and sub-stellar objects which suffer high extinction and nebulosity. **In ONC, about 76% of the originally proposed targets have been obtained during the MMIRS run in 2015B, 2016A, & 2017A. In this proposal we request 2 nights to use MMIRS to obtain complete sample.**

Why Orion Nebula Cluster and NGC 1977? The ONC is one of the best studied star forming regions at a distance of $\sim$414 pc (Menten et al. 2007), and *the* prime target for studies of disk evolution in high UV radiation environment. The Trapezium Cluster at the center of Orion nebula is suggested to be the closest analog of the birth place for the Solar system (Adams 2010). An O6 star, θ^1 Ori C, is the main ionizing source in ONC providing enough UV photons to its environment, and photoevaporating protoplanetary disks (*proplyds*) have been well studied in this region. ONC has been observed extensively in multi-wavelength imaging and optical spectroscopy (e.g., Hillenbrand et al. 1997, 2013). *However, young stellar objects (YSOs) at the very central region of the ONC, where photoevaporation is expected to be the strongest, need better characterization using IR spectroscopy, because of high extinction and strong nebulosity.* About 30% of the sources out of total 1,009 sources have spectra from other studies within the MMIRS field of view ($4' \times 7'$). However spectral resolution is low, and there is no accretion rate measurements. Without information on stellar properties (spectral types and stellar masses) the investigation on disk mass/stellar mass dependence study would not be possible (for example, Eisner et al. 2008 studied disk masses in ONC, however their work was hampered by a lack of spectral types). Unlike ONC, its sibling NGC 1977,

$\sim$30$'$north of ONC, is poorly studied, yet we have recently discovered *proplyds* around 42 Ori (B1V). This UV environment is weaker than that in ONC providing the best star forming region to study differences of UV radiation environment. NGC 1977 harbors at least 7 proplyds (Kim et al. 2016), spectacular jets and outflows, (Bally et al. 2012) and high disk fraction, making it very rich environment to study YSO evolution. We propose to use MMIRS in multi-object mode to obtain H&K band spectra of total $\sim$180 YSOs in the central ONC and NGC 1977, which will yield complete census for 9.5<K<15.5mag (see the left panel of the figure). Multi-object near infrared spectroscopy using MMIRS will provide ideal set of spectra of these embedded YSOs in the heart of ONC to characterize stellar properties and estimate accretion rates. We will obtain complete census of YSOs in central ONC for targets with 9.5<K<15.5mag. Stellar density of ONC is high ($n \sim 2 \times 10^4 pc^3$, Hillenbrand & Hartmann 1998), therefore multi-object spectroscopy is the best to observe these targets. Figure (right) is $H-K, K$ color-magnitude diagram of the sources in the Trapezium cluster, using photometric catalog by Hillenbrand & Carpenter (2000). We expect to have complete sample down to $K \sim 15.5 mag$ ($M \sim 0.08 M_{\odot}$ for $A_K = 2\ mag$).

Immediate Objective Identifying disk dispersal is a key step in characterizing boundary conditions for planet formation and essential for developing reliable models. Multiple mechanisms may play roles in the disk dispersal, but their relative importance could not be determined for two reasons: i) no large enough homogeneous set of disks have been studied to allow statistical verification of the predictions of different disk dispersal mechanisms; and ii) the stellar atmospheres and disk masses of existing samples have not been characterized accurately enough to allow statistical comparisons, due to high extinction etc. typical to very young clusters. Our scheduled ALMA observations (PI Eisner) in Cycle 3 will map the central part of ONC. The ALMA data will be used to estimate disk masses of YSOs together with multi-wavelength data. We propose here to combine an ambitious ALMA disk survey with MMT/MMIRS observations to establish the first complete census of disks and precise stellar parameters in a nearby star-forming region, the necessary dataset to test the key disk dispersal mechanisms.

Targets Combined with this proposed observation, we will obtain IR spectra for total 416 YSOs in the central part (See the left panel in Fig. 1) of ONC. Our observations will complete YSO census in central region of ONC which suffer high extinction. With $H\&K$ band spectra we will characterize stellar properties, estimate accretion rates, and constrain circumstellar disk lifetime. **Our goals** are: a) determine spectral types (using atomic lines, e.g., Fe 1.56259 and 1.56362 μm and OH doublet at 1.56314 μm); b) derive ages and masses using H-R diagrams and isochrones based on their spectral types; c) estimate accretion rates using Brγ line ($n = 7 \rightarrow 4, \lambda = 2.1661 \mu$m); d) investigate frequency of stars with circumstellar disks (disk frequency) as a function of stellar mass and ages; e) study disk frequency and disk mass as a function of distance from ionizing sources, an O6 star ($\theta^1 C$ Ori).
With proposed observations and newly obtained ALMA data we will constrain disk mass and disk fraction as a function of projected distance from the O star in ONC. We will follow the approach by Balog et al. (2007) in performing Monte-Carlo simulation to account for distances of the YSOs random walking around the ionizing O star. We will compare disk lifetime from other Orion star forming regions under various environments and ages, for example Lynds1641, NGC1977, and NGC1980. For example Lynds 1641 (age$\sim$1.5Myr; Fang et al. 2009; 2013) is in the same molecular cloud (same distance and metallicity), but under very different environment (no nearby O star), therefore we can separate other effect, and study the role of environment by comparing ONC and Lynds1641. NGC1980, just south of ONC, has ionizing sources, but may be slightly older $\sim$2 Myr (Fang et al. 2017).

References: Adams 2010, ARAA, 48, 47; Alexander et al. 2014, Protostars and Planets VI, 475; Alexander & Pascucci 2012, MNRAS, 422, L82; Artymowicz & Lubow, 1994, ApJ, 421, 651; Bally, J. et al. 2012, ApJ, 756, 137; Balog et al. 2007, ApJ, 660, 1532; Baraffe et al. 1998, A&A, 337, 403; Boss 2002, ApJ, 576, 462; Davies et al. 2013, A&A, 558, AA56; Eisner et al. 2008, ApJ, 683, 304; Fang et al. 2009, A&A, 504, 461; Fang et al. 2013, A&A, 549, AA15; Haisch et al. 2001, ApJL, 553, L153; Hartmann et al. 1998, ApJ, 495, 385; Hernández et al. 2007, ApJ, 662, 1067; Hillenbrand 1997, AJ, 113, 1733; Hillenbrand et al. 2013, AJ, 146, 85; Kim et al. 2005, AJ, 129, 1564; Kim et al. 2016, ApJL, 826, 15; Mann et al. 2015, arXiv:1501.06512; Menten et al. 2007, A&A, 474, 515; Hillenbrand & Hartmann 1998, ApJ, 492, 540; Hillenbrand & Carpenter 2000, ApJ, 540, 236; Ingraham et al. 2014, ApJ, 782, 8; Pascucci & Sterzik 2009, ApJ, 702, 724; Sicilia-Aguilar et al. 2006, ApJ, 638, 897; Zsom et al. 2011, A&A, 534, AA73

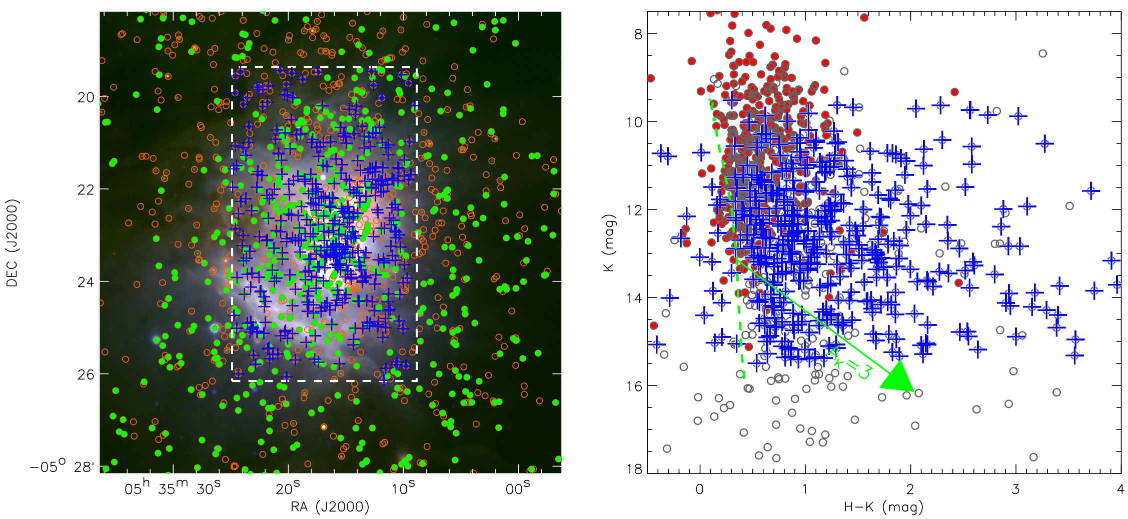

Figure 1: **Left**: Color composite near-infrared (JHK_s) 2MASS image of the central part (the Trapezium Cluster) of the ONC. The circles (open and filled) are all the stars in the cluster found by Hillenbrand &Carpenter (2000). The filled circles are the ones which have been observed with spectroscopy, and the open circles are without spectroscopic data. The big box ($4' \times 7'$) enclose the region that we propose for the MMIRS observation. Within the box, there are $\sim$1000 sources, and about 65%. The plus symbols mark the sources which we propose to observe them with MMIRS. The MMIRS field covers the ALMA mapping field. **Right**: The H-K vs K color-magnitude diagram for the sources (open and filled circles) in the Trapezium cluster using the photometric data from Hillenbrand &Carpenter (2000). The symbols (open circles, filled circles, and pluses) are same as in the left panel. The dash line are the 1 Myr isochrone of the pre-main sequence stars from Baraffe et al. (1998). The arrow is the extinction vector with $A_K = 3$. The arrow also divides our select targets (pluses) into stellar population and substellar population.

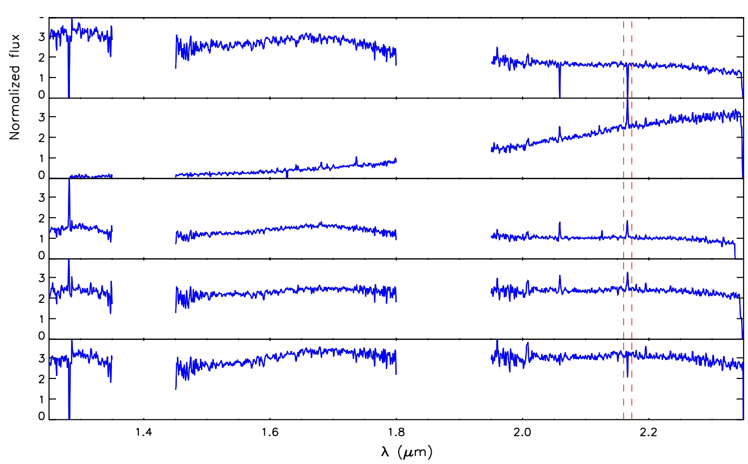

Figure 2: We show example spectra from our previous MMIRS run from Dec 30, 2015-Jan 2, 2016. Br γ emission line, indicative of YSOs, is from various sources (between red dashed lines). Data reduction of recently obtained spectra is on-going.

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)***

Our science goals require that we determine stellar properties and accretion rates for total 416 sources. In this proposed observations we will obtain about **100** targets of the sample in the center of ONC, and 80 in the center of NGC 1977. Together with previously observed 2015B and 2016A, 2017A observations we will obtain near-IR spectra of 416 targets in ONC. The most ideal instrument for these observations is MMT/MMIRS. We have **310 out of total 416 targets** selected for this program within the MMT/MMIRS field of view ($4' \times 7'$). All our targets have K-band magnitudes brighter than 15.5 mag. Our goal is to measure the equivalent widths of a number of photospheric absorption lines to characterize stellar properties and the Brγ emission line for accretion rate estimate. From these measurements, we will determine the spectral type of the star as well as the continuum veiling using methods developed by Luhman & Rieke (1998,1999). We will also use the telluric standard stars to do the flux calibration. Thus our spectra will be flux calibrated from which we can obtain the Brγ emission line luminosity. Then we can estimate the accretion rate from the luminosity in Brγ emission line using the relation from Alcalá et al. (2014).

Since we need to estimate accretion rate from the Brγ emission line, we need high SNR spectra around the Brγ emission line. We have used the MMIRS exposure time calculator to calculate the needed observing times under typical observing condition, and have chosen our exposure times such that we will get $SNR >$ 230 for the targets with K<10.5 mag, $SNR > 170$ for the targets with K<11.5 mag, $SNR > 130$ for the targets with K<12.5 mag, $SNR > 95$ for the targets with K<13.5 mag, $SNR > 54$ for the targets with K<14.5 mag, and $SNR > 24$ for the targets with K<15.5 mag. At these SNRs, our detection limits at 3σ confidence correspond to an accretion rate of $\sim$ 1–3×10^{-9} $M_{\odot} yr^{-1}$ for young stars in Orion. The accretion rates of most of young stars at the age of the Trapezium cluster (1 Myr, Muench et al. 2002) are expected to be larger than 1×10^{-9} $M_{\odot} yr^{-1}$ for young stars with masses larger than 0.1, $M_{\odot}$ (Natta et al. 2006). Thus, with the achieved SNR we will be able to well measure the accretion rate of the vast majority of the targets, and put stringent upper limits on the very weak accretors. Also, the expected SNRs is adequate for spectral typing.

We need both coverage of the H and K-band to simultaneously measure all photospheric lines of interest and Brγ emission line, as well as reasonable spectral resolution to avoid line-blending and increase sensitivity.

We divide our targets into different fields according to their H- and K-band magnitude. To observe all the targets, we have 12 fields to be observed this time. Based on the instructions in the MMIRS user manual overhead time for each field is $\sim$25 minutes. Therefore total 12 field observations will require 10.5 hours.

Including on-source exposure, overhead, and calibration, we requested a total 1 night of MMIRS during the 2017B semester. **We requested 2 nights to use MMIRS to complete the proposed observations to carry out science goals proposed in this proposal.**

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**)*

This program is part of the Earth in Other Solar Systems (EOS), NASA's Nexus for Exoplanetary System Science program (PI: Apai). This proposal is continuation of previously accepted proposal in 2015B and 2016A. Since we have not obtained complete sample, we are resubmitting this proposal to obtain remaining **50%** of the target.

We request 2 nights of observing run to observe one of the three EOS team's target fields, Orion Nebula Cluster. We were awarded 1 night to use MMIRS during 2015B, 2 nights in 2016A, and 2 more nights in 2017A, however due to combination with weather loss and mask issue in 2016A we have about 180 more data to obtain spectra in order to complete observations of total $\sim$416 targets which we have already made masks. In order to carry out the proposed science with the selected targets, which have been observed with ALMA, we request 2 more night to use MMT/MMIRS.

We have obtained *ALMA data recently* of our ONC target field. Given the EOS project's timeline the MMT observations should be carried out as soon as possible 2017B the latest, to allow timely publication while funding is available for this project. Our result from this proposed observations will be used for the next steps by the teams within the EOS team.

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**)*

⋆ *Characterizing YSOs in the Heart of the Orion Nebula Cluster using MMT/MMIRS multi-object spectroscopy* (PI: J. S. Kim, Co-Is: M. Fang (SO), I. Pascucci (LPL), J. Eisner (SO), D. Apai (SO/LPL), L. Allen (NOAO)). One night of MMIRS time was awarded in 2015B and 2 nights in 2016A from December 31, 2015 to January 2, 2016. For our 2016A run, masks could not be made due to holiday schedule, therefore we used MMIRS in ingle slit spectroscopy mode. We were awarded 2017A run to complete the proposed MMIRS observations, but bad weather condition left about 180 sources that we planned, with for 2017A runs. We have published part of the data for the lowest mass proplyd found in ONC from this dataset (Fang et al. 2016, ApJL, 833, 16). The ALMA Cycle 2 paper on ONC has been published (*J. Eisner et al. 2017, ApJ, 826, 16*), and our team is analyzing the recently obtained ALMA data.

Near-IR Variability Studies of Star Forming Regions: Finding Very Low Mass Young Stellar- and Sub-Stellar Objects (Year1 (2014) is completed, and Year 2 (2015) observations were carried out only for 20%. For Year 3 (2016), we only obtained 10 epoch data for IC 1396A). (PI: J. S. Kim, Co-Is: George Rieke (SO), Klaus Hodapp (University of Hawaii), Luisa Rebull (SSC), John Stauffer (IPAC)). Our year 1 data have been successfully obtained for all regions (IC 1396A, NGC 1977 NGC 1980). Only small portion of data were obtained for year 2 (2 epoch only) The first look data for for most of the observations during year 1 was successful. Few images for Orion show trailing problem. For most complete data set was taken for IC 1396A, we are analyzing the UKIRT data, and a paper is in preparation (Meng et al. in prep.).

Near-IR spectroscopic survey of young stars associated with the feedback driven star forming region AFGL333 in W3 complex (PI: J. S. Kim, Co-Is: Jessy Jose, Greg Herczeg) In 2017A, we were awarded 1 night (bright) to use MMT/MMIRS for this project. Due to bad weather condition, we obtained about 30% of the proposed data. The data reduction and spectral extraction was done and the data are being checked for telluric correction, etc. The S/N of some of the objects were too low due to cloudy observing condition.

The Spectroscopic Initial Mass Function of a Young Star Cluster that Just Evolved from its Parental Cloud (PI J. S. Kim with members of the SDSS IV, APOGEE-YSO team) We were awarded 1 night to use Hectospec for YSO targets in 25 Ori. Two fields of the data were taken, yet only about 60% of the observations were carried out. The obtained data were reduced, and are being analyzed. Spectral typing has been carried out.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

In the 2017A run, we have made mask for 8 fields which have been observed with MMT/MMIRS. However, towards 3 fields of them, the telluric observations were not useful for telluric correction, which is either due to the large airmass difference between the telluric observations and scientific observations, and/or due to the bad pointing to the telluric standards. Many of the sources were not detected. In this proposal, most of targets in ONC are from these three fields we need to re-observe, and 80 targets from NGC 1977 where we study weaker radiation environment than in ONC. Both ONC and NGC 1977 are critical part of our NExSS team team, Earth in Other Solar systems (PI Apai).