# OBSERVING REQUEST
**University of Arizona Observatories**

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

# Near-IR spectroscopic survey of young stars associated with the feedback driven star forming region AFGL333 in W3 complex

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**Abstract of Scientific Justification**

Most stars form in clusters and a large fraction of them form near massive stars in young clusters. The feedback from OB stars affects protoplanetary disk evolution of neighboring young stars, and the planet formation processes. Similarly, feedback from massive stars plays an active role in the subsequent evolution of their parent molecular clouds. Feedback can trigger the birth of new generations of stars and can also inhibit star formation by clearing away the dust and gas. This proposal seeks to quantify the effect of feedback towards AFGL333, in the W3 giant molecular cloud complex, one of the most massive star forming regions, which is considered to be influenced from the massive stars in the nearby W4 super bubble. AFGL333 contains two sub-regions, one shows the signatures of feedback driven star formation and the other shows no signs of feedback activity. Here we propose for the H + K band spectroscopy of the candidate young stellar objects identified within these two sub-regions of AFGL333 using MMIRS of MMT. Our goal is to accurately measure the stellar parameters (age, mass, accretion rate, disk lifetime) and star formation parameters (Initial mass function, star formation efficiency, star formation rate) of both the feedback and non-feedback regions in AFGL333, and compare their properties to understand the effect of stellar feedback on the star formation processes of the molecular cloud. High extinction to massive star forming regions severely biases optical studies and hence NIR spectroscopic observations are essential. We have an approved *Chandra*-ACIS program on the same target and the proposed observations will be complemented with the X-ray properties of the young stellar objects. **This is a resubmission of an accepted proposal in 2017A. Only 30% of the observations has been done due to weather loss.**

**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 | * | | 1 | bright | Nov-Dec | Oct-Dec | yes | yes |

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

*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 | BRC5 | 02:29:09.8 | +61:33::31.0 | |
| 2 | AFGL333-NW1 | 02:27:13.8 | +61:37::26.6 | |

**Approval for Instrument Use from PI:** PI of the MMIRS (Brian McLead approved it via email.

**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

Two main modes of star formation are i) spontaneous star formation, which is the natural collapse of clumps and cores generated by the large-scale supersonic turbulence of the ISM (see e.g. Mac Low & Klessen 2004) and ii) triggered star formation, which is the compression of pre-existing cloud material due to the external feedback (see e.g. Elmegreen 1998). On large scales star formation is triggered from compression by Galactic spiral arms, on intermediate scales from compression by supernova remnant super bubbles in starburst complexes, and on small scales from compression by expanding H II regions (Elmegreen & Palous 2007). The formation of 14-30% of massive stars in the Milky Way is triggered by expanding H II regions, confirming its importance in Galactic star formation (Thompson et al. 2012).

One of the unsolved questions in the field of star formation concerns the effect that environment and the feedback from massive stars may have on the star-formation processes. For example, the lifetime of protoplanetary disks is likely to be shortened by the strong stellar winds and ultraviolet radiation from massive stars, which can potentially impact the planet formation in such protoplanetary disks (Kim et al. 2016). Similarly, stellar feedback can trigger the birth of new generations of stars and can also inhibit further star formation by clearing away the dust and gas (Bisbas et al. 2011, Walch et al. 2013). Numerical simulations show that the feedback driven star formation tends to increase the star formation efficiency, rate and the total number of stars formed compared to the quiescent regions (e.g Dale et al. 2007). However, the effect of external feedback on the characteristics of newly formed stars as well as on the form of initial mass function and star formation efficiency are yet to be understood. A comparative analysis of star forming regions experiencing feedback from massive stars (e.g., triggered or sequential star formation mode) with respect to spontaneously formed young stars without massive star feedback may help distinguish these two processes.

Investigating the effect of stellar feedback on the star formation properties of a cloud is observationally challenging, because it is hard to disentangle spontaneous and triggered stars of a molecular cloud. However this question can still be approached by selecting morphologically simple clouds which strongly suggest a feedback and identifying weak- to no-feedback from massive stars. Comparing the properties of young stars and disks in such two different kind of environments will provide important clues to understand feedback processes in star formation. The radiative feedback of massive stars creates pillars, globules and elephant trunks at the interface between H II regions and molecular clouds (Bisbas et al. 2009). Therefore, these structures are the potential sites to study induced star formation due to compression by ionisation/shock fronts from massive stars (Getman et al. 2012; Sharma et al. 2016). Proper membership selection, accurate estimation of stellar parameters such as age, mass, accretion rate etc. will distinguish the properties of the feedback driven stars and the spontaneously formed ones. *We propose to obtain the near-IR (NIR) spectroscopic observations of the candidate young stellar objects within two sub-regions of AFGL333 cloud complex, where, one shows the signatures of feedback driven star formation and the other one shows no signs of feedback activity. Our goal is to compare the star formation properties (IMF, star formation efficiency and rate, disc accretion rates) of both regions in a uniform and unbiased manner and to understand the effect of stellar feedback on the star formation processes of the molecular cloud.* We have an approved *Chandra*-ACIS-I program on the same target region during the cycle 18. The proposed NIR spectroscopic observations will be complemented with the X-ray based selection of disked and diskless member stars in combination with the existing optical and IR imaging data sets.

**Proposed targets**: The regions we propose are located in AFGL333, which is part of the W3 giant molecular cloud complex, one of the most massive, relatively distant ($\sim$ 2 kpc) star forming regions which is evolving under the influence of strong stellar winds and radiation from the massive stars in the nearby W4 super bubble. AFGL333 contains a bright-rimmed cloud (BRC 5) and several stellar aggregates (See Fig.1; Jose et al. 2016). BRC5 with a cometary morphology (see Fig 1) have several finger-tip like features facing the expanding W4 H II region. The bright rim around the cometary cloud surface seen in H$\alpha$ (Fig 1. right panel) as well as the free-free radio continuum emission at the cloud surface (NVSS survey) are the strong signatures of ongoing photo-evaporation/ionization at the surface of BRC5, which confirms that it is under the potential of the strong stellar winds/radiation from the $\sim$ 60 OB type massive stars in W4. The collective stellar wind energy from the most massive, 9 O type stars, is $\sim 3 \times 10^{37}$ ergs/s (Normandeau et al. 1996), and radiation energy are sufficient enough to structure the surrounding molecular cloud and affect the star formation in them (Bisbas et al. 2011). This make BRC 5 as one of the rare regions (at this distance), undergoing evolution in the strongest pool of radiation from massive stars and hence BRC 5 can be considered as a representative target to study the feedback driven star formation.

On the other hand, the AFGL333-NW1 (Jose et al. 2016) is a newly identified young cluster within AFGL333 (see Fig. 1). This cluster is $\sim$ 12 pc away from the nearest O/B stars in W4, and hence the chances of being externally influenced from the massive stars of W4 are negligible. It lacks any morphological signatures of feedback influence from massive stars. The earliest spectral class within the cluster is a B5V star (Kiminki et al. 2015), hence the internal feedback is negligible. Therefore, AFGL333-NW1 can be considered as evolving in a non-feedback environment and is an ideal target to compare with the properties of BRC5.

Both BRC5 and AFGL333-NW1 are of roughly similar age ($\sim$ 2-3 Myr) with average reddening of $A_V \sim 5$ mag. Both have sufficient number of stars ($\sim$ 50%) with circumstellar disk around them (Jose et al. 2016). A comparative analysis of stellar characteristics as well as star formation parameters of these two regions is an important step to understand the feedback driven versus spontaneous mode of star formation.

**Immediate Objectives**: Using MMIRS, we will obtain the spectra of each member stars within the regions and will produce the spectral types. The photospheric temperature, extinction, and luminosity measured from the NIR spectroscopy analysis will yield estimates for stellar ages and masses based on pre-main sequence evolutionary models (e.g. Baraffe et al. 2015). Equivalent width of Br$\gamma$ will be used to estimate the accretion parameters (Alcala et al. 2014). The correlation of accretion parameters with the local values of Far and Extreme ultraviolet radiation fields will be analyzed (Kim et al. 2016). Accurate measurement of stellar parameters will be used to estimate the total stellar mass, form of initial mass function, star formation efficiency and star formation rates. The uniform and unbiased approach along with the *Chandra*- X-ray data and previously obtained optical and IR imaging data will yield powerful new insights on the distribution, mass budget, time scales, physical conditions and star formation efficiency and rates of both regions. A comparative analysis of the stellar properties and star formation parameters will be used to measure the net effect of stellar feedback on star formation process. We will compare the observed star formation properties of the regions with the proposed theoretical star formation relationships that describe the variation of star formation rates with the amount of gas processed over key timescales, to discuss the relevance of feedback driven star formation. NIR spectroscopy is essential for this study as the candidate member stars are relatively faint and extinction is high towards the region.

**Team**: The PI (Serena Kim) and Co-I (Jessy Jose) are experts on various photometric studies of triggered star forming regions and will lead the analysis. The Co-Is, (G.J Herczeg and Min Fang) are experts in analyzing low-resolution spectra and have extensive expertise in accretion and photospheric properties of young stellar objects. The PI and Co-I (Min Fang) have previous experiences in using various optical/NIR spectroscopic observations/data from MMT.

**This is a resubmission of a successful program in 2017A. Only $\sim$30% of data were taken due to weather loss.**

**References:**

**Alcala J.M.** et al. 2014, A&A, 561, 2; **Baraffe, I.** et al. 2015, A&A, 577, 42; **Bisbas, T.G.** et al., 2009, A&A, 497, 649; **Bisbas, T. G.** 2011, ApJ, 736, 142; **Dale, J. E.** et al. 2007, MNRAS, 377, 535; **Dale, J.E.** et al., 2015, MNRAS, 450, 1199; **Elmegreen, B. G.** 1998, Origins, 148, 150; **Elmegreen, B.G.** & Palous, J., IAUS, 2007, 237; **Getman, K.V.**, et al. 2012, MNRAS, 426, 2917; **Jose, J.** et al. 2016, ApJ, 822, 49; **Kim, J.S.** et al. 2016, ApJ, 826, 15; **Kiminki, M** et al. 2015, ApJ, 813, 42; **Mac Low, M.-M** et al. 2004, 76, 125; **Sharma, S.** et al. 2016, AJ, 151, 126; **Thompson, M.A.** et al., 2012, MNRAS, 421, 408; **Walch, S.** et al. 2013, MNRAS, 435, 917;

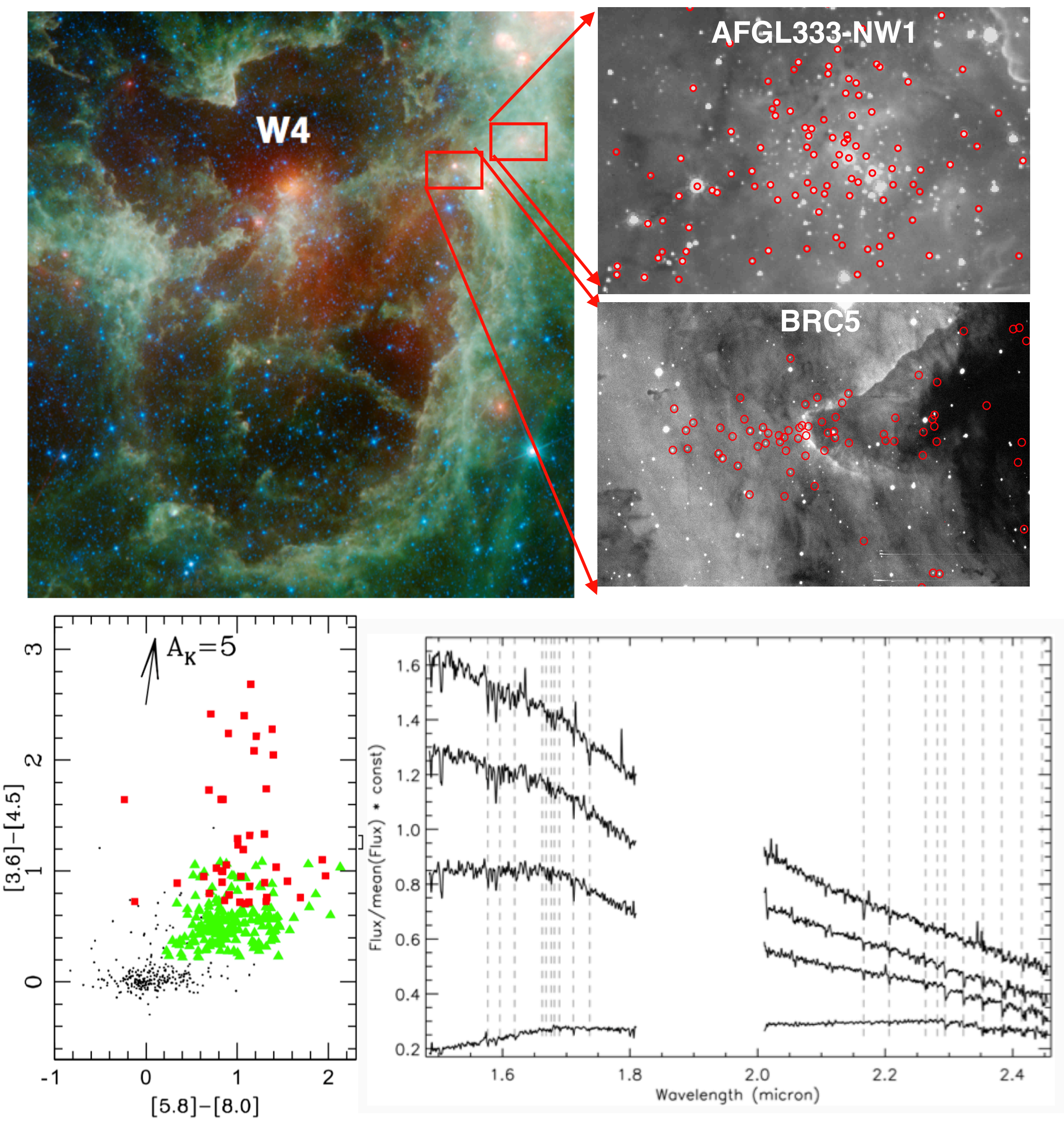


Figure 1: *left:* Color composite image of the W4 super bubble made using the *WISE* images and the two proposed $4' \times 7'$ area are highlighted in the box. Candidate young stellar objects identified are marked in red circles. *bottom left:* Mid-infrared color-color diagram used to select the candidate young stellar objects (red: Class I, green: Class II). *bottom right:* Sample NIR $K$-band spectroscopy of massive stars identified in the RCW 34 complex using the VLT/SINFONI spectrograph (Bik et al. 2010).

**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**)*

We propose to obtain MMIRS spectra of candidate young stellar objects within two sub-regions of AFGL333 to characterize the stellar properties of the young stellar objects using photospheric absorption lines. The luminosity of Br$\gamma$ emission line will be used to estimate the accretion rates using the relation from Alcala et al. (2014).

The $K$-band magnitude range of candidate young stellar objects is in the range $\sim$ 11 – 15 mag. For the assumed age of 1 Myr (Siess et al. 2000), distance (2 kpc), reddening ($A_V$= 5 mag) and $K$- band magnitude of 11 – 15 mag, spectra will cover stars from 0.5 – 1.5 $M_{\odot}$. Based on NIR-MIR photometric analysis using NEWFIRM and *Spitzer* images, there are 35 and 60 IR excess sources within the two proposed sub-regions (Jose et al. 2016). The boxes marked in Fig. 1 represent the proposed areas for the observations and most of the IR excess sources are found to be confined within the $\sim 4' \times 7'$ field of view of MMIRS. The disk fraction estimated in these regions are $\sim$ 50% (Jose et al. 2016). The diskless member stars will be identified based on the *Chandra* X-ray observations. In this semester, we propose for disked sources (total 95 targets) within AFGL333 and in the next semester, we plan to propose the diskless sources which will be identified based on the *Chandra* data.

We plan to use the MMIRS in multi-slit mode using $HK3$ filter in combination with a slit width of $1''$ and R=1500. We need both H and K-band coverage to measure all photospheric lines simultaneously along with Br$\gamma$ line. The above combination along with the resolution is needed to avoid line-blending and to increase sensitivity. We will use slit length of $7''$, which allows sufficient slit length for nodding and sky subtraction. Considering the FOV of $4' \times 7'$ for MMIRS, the maximum number of slits which can fit in one mask is 60. Considering the crowding of the field, we expect that $\sim$ 20-30 sources can fit in one mask.

According to MMIRS exposure time calculator, using HK3 grism of MMIRS, slit width of 6 pixels, seeing $=1''$, a 15 mag star in K-band will yield S/N=25 at 2.1 $\mu$m for an exposure of 60 min and for a 13 mag star for similar S/N, require 6 min. S/N $\sim$ 25 is sufficient to measure the Br$\gamma$ emission line and photospheric absorption lines. We will split the expsoures into short and long to cover the entire magnitude range as well as the long exposure will be split in to two 30 min. slots to have a telluric standard observations in between.

For BRC5, we will have one mask each for bright stars (6 min) and faint stars ($2 \times 30$ min) and for AFGL333-NW1, one bright star mask (6 min each) and two faint star masks ($4 \times 30$ min), therefore we will have total 8 pointing to cover both regions. Based on the instructions in the MMIRS user manual overhead time for each field is $\sim$ 25 minutes.

Including on source integration and overhead we request for 7 hours of observing time for this project. We have made total 6 masks last time in 2017A. We have only observed bright masks and one faint targets. But the faint targets need to be re-observed. We have three masks that were already cut, and ready for us to use. We will make one more mask to complete the survey of the region.

**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**)*

There was 1 night of MMIRS time awarded during 2017A. However, due to weather loss, we could get data for about 30% only, mostly bright targets for one of the target fields (BRC). some of the faint sources have suffered cloudy night condition. The obtained MMIRS data were reduced, but we are working on reduction improvement especially with better telluric correction. Due to bad weather S/N of some spectra are too low, therefore we need to retarget some of the sources We therefore request another 1 night (0.75 night) in order to obtain the complete dataset we proposed.

This program (PI Kim) is a more focused follow up program somewhat related to the PI's previous NSF proposal, which used Hectospec for large region of W3 and W4 (Kiminki et al. 2015, ApJ, 813, 42). This proposal focuses on two very small regions of (MMIRS FOV) presented by our recent paper Jose, Kim, Herczeg et al. (2016, ApJ, 822 49).

*Chandra* X-ray observations (awarded, PI Kim) for the Cycle 18 are planned for the proposed region. The X-ray data will be used in combination with imaging and spectroscopic data to sample member young stars with/without disks to carry out the proposed science.

*GMRT-India*: Radio continuum observations were obtained (PI: Jose) at low frequencies (610 and 1280 MHz) as part of the Cycle 27 for this region. The data have been processed and will be used to estimate the ongoing photo-ionization rate at the cloud surface of BRC5 and thus to quantify the amount of feedback effect.

**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)***

⋆ *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 look too low due to cloudy observing condition.

*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 in 2015B, 2 nights in 2016A from December 31, 2015 to January 2, 2016, and 2 more nights in 2016B (December 20-21, 2016) have been awarded for this program. For the 2016A run, masks could not be made due to holiday schedule, therefore we used MMIRS in single slit spectroscopy mode. About 50% of data were obtained. During the upcoming MMIRS run (two nights in December 2016), we plan to complete our planned observations of YSOs at the very center of the Orion Nebula Clusters. An ALMA Cycle 2 paper on ONC has been published (*J. Eisner et al. 2016*), andMMIRS data analysis is on-going. This program is part of the NExSS EOS program (PI: Apai). Two related papers of ONC targets have been submitted (Fang et al. 2016a, ApJ; Fang et al. 2016b, ApJS).

*Near-IR Variability Studies of Star Forming Regions: Finding Very Low Mass Young Stellar- and Sub-Stellar Objects (2014, 2015, and 2016).* (PI: J. S. Kim, Co-Is: George Rieke (SO), Klaus Hodapp (University of Hawaii), Luisa Rebull (SSC), John Stauffer (IPAC)). Our year 1, 2 data have been successfully obtained for more than 50% during 2014-2015. During 2016A more observations of IC 1396A (30hr) have been carried out. We are awaiting for the data to be available to the team. The analysis for the data we have obtained from years 1 and 2 are on-going.

⋆ *Hectospec Observations of Young Stars in the W3/W4 Star-Forming Regions* (PI: J. S. Kim.) This proposal is a follow up program which focuses on only two very small regions of the previous NSF program (PI Kim). This Hectospec observing runs are not directly related to this new proposal to use MMIRS, but have more focused science goals using carefully selected two small regions located in between W3 GMC and W4 HII region. which are still related to the science goals of Kim's previous NSF program, which is being developed as a follow up NSF proposal. A total of 8.67 nights were awarded during 2008-2011, 3 more nights during 2012A, and 2.5 more nights during 2013A to do follow-up spectroscopy of candidate PMS stars for the W3/W4 regions. Observations during 2012 and 2013 were mostly unsuccessful due to instrument problems (robotic arm failures) and weather. Most of the bright source spectra in W4 data were reduced, spectral typed, and are currently being analyzed with optical, infrared, and X-ray data. All the data in the W3 have been reduced and spectral typing and analysis on high mass stars to intermediate mass stars was published. Spectra of the low mass objects in specific clusters are being analyzed. – Preliminary results for W3 were presented at the January 2010 and May 2011 AAS meetings (*Kim, J. S., et al. 2010, BAAS, 42, 259; Bagley, M. M., et al. 2011, BAAS, 43*). – One paper using Hectospec data on W3 have been published for high mass stars in the W3 (*Kiminki, Kim, Bagley et al. 2015, ApJ, 813, 42*), one related paper is published on W3-AFGL333 (*Jose, Kim, Herczeg et al. 2016, ApJ, 822 49*), and one paper on IC 1795 cluster is in preparation (*Kim et al., in prep.*). Spectroscopic data analysis of W4 region using Hectospec data are on-going (*Wilking, Kim, Wentzel et al. in prep.*) Results on AFGL333 has been presented during the Astrobiology conference held in Tucson, March 2014, during two talks given at Institute of Astronomy, University of Cambridge (spring, 2016), colloquium at University of St. Andrews (June 2016), and in Origins seminar (Fall 2016) at Steward.

**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**)*

This project is related to the PI's previously funded NSF AAG project. Although the NSF funding has ended, this MMIRS dataset for the embedded region and highly reddened sources are critical for the follow-up NSF proposal.