OBSERVING REQUEST
University of Arizona Observatories

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

Searching for Kinematic Substructure of the Core Cluster IC 1805 in the Cas OB6 Association

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Abstract of Scientific Justification

Kinematic substructure of young stars and gas in a star forming region connotes not only the initial conditions of star formation but also early dynamical evolution of star forming regions (SFRs). For this reason, several recent studies have tried to identify kinematic substructure in nearby SFRs, and they estimated the virial state of those SFRs from the velocity dispersion of stars and gas. Unlike these quiescent SFRs, massive SFRs would have more complicated substructure, because feedback from massive stars influences their surrounding material in both positive and negative ways. We intend to investigate the kinematic substructure within the massive SFR W4 located in the Cas OB6 association. The core cluster IC 1805 in W4 contains eight massive O-type stars, and the radiation field of these stars sculpted a number of small gas structures as well as a huge H II bubble. All the O-type stars are concentrated within 8.4 pc from the cluster center, whereas a number of lower-mass stars are spread over a wider region (30 pc $\times$ 31 pc). These facts indicate that two different mechanisms, spontaneous and feedback-driven star formation, are involved in the formation of this SFR. We will measure the radial velocities of 357 young stars ($V = 9 - 19$ mag) and the ionized gas from 480 fiber positions, identifying subgroups with different velocity fields from a position-position-velocity diagram, channel maps, etc. A spectral resolution ($\frac{\lambda}{\Delta\lambda}$) of about 16,000 is sufficient to resolve the velocity difference larger than 1 km s^{-1} among stars, while a higher resolution ($> 30,000$) is required to analyze the emission line profiles of the ionized gas. We will be able to constrain the build-up process of the Cas OB6 association from observations with the high resolution multi-object echelle spectrograph Hectochelle if MMT is accessible for a night in 2017B.

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	MMT	f/5	Hectochelle			1.0	bright	Oct–Nov	Sep–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Unusable date: Jul–Aug, Reason: Our target (R.A. = 02:32:42.00, Dec. = +61:27:00, 2000) is inaccessible.

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	357 member stars in IC 1805	02:32:42.0	+61:27:00.0	Stars, $V = 9 - 19$ mag
2	480 fiber positions	02:32:42.0	+61:27:00.0	Ionized gas, variable line strength

Approval for Instrument Use from PI: ______________________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

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

We intend to figure out the build-up process of the Cas OB6 association. The radial velocities (RVs) of young stars and ionized gas within the massive star forming region (SFR) W4 which is a major part of the OB association will be measured. The distribution of their RVs provides not only essential information on the initial condition of star formation but also an opportunity to study early dynamical evolution of SFRs. It is well known that molecular clouds have a highly hierarchical substructure – their internal velocity dispersions showed good correlations with the size and mass of the clouds (Larson 1981). Star formation taken place in the hierarchical substructure also shows a self-similar nature (Larson 1991; Elmegreen 2011). Imaging surveys have identified a large number of young stellar objects in several SFRs using *Spitzer* space telescope and Wide-field Infrared Survey Explorer. These observations showed that most of the surveyed SFRs are composed of numerous subclusters with different sizes and a halo population (Koenig et al. 2012; Gutermuth et al. 2009; Sung et al. 2009, etc.). Several theoretical studies argued on a basis of numerical experiments that that substructures and subvirial conditions at the early stage of star formation can result in mass segregation within protoclusters as a consequence of dynamical evolution on a very short timescale (Moeckel & Bonnell 2009; Allison et al. 2009).

Recently, an extensive RV survey for pre-main sequence (PMS) stars in nearby low-mass SFRs has been initiated as an ancillary program of the Sloan Digital Sky Survey III (Cottaar et al. 2014). The young SFR NGC 1333 (1 – 2 Myr) appeared to have reached virial equilibrium, and the velocity dispersion of embedded stars is coincident with that of diffuse gas (Foster et al. 2015). Stars in the slightly older SFR IC 348 (2–6 Myr) exhibited a super-viral velocity dispersion (Cottaar et al. 2015). In addition, it appeared that two subgroups are converging along the line of sight. Star formation took place along a filamentary gas structure in the Orion A molecular cloud, and a large age spread among PMS stars was observed across the cloud (Da Rio et al. 2016). Da Rio et al. (2017) found a velocity variation of 10 km s^{-1} along the gas filament. They could also identify kinematic substructure among the member stars and suggested that this SFR can form a marginally bound cluster given its virial parameter. This survey provided strong constraints on the dynamical evolution state of subgroups as well as the initial velocity dispersion of stars.

We expect that massive SFRs may have a more complicated substructure and a history of drastic dynamical evolution. Massive O-type stars can blow out remaining gas through their strong stellar wind and ultraviolet radiation, and thereby create a cavity in the central part of an H II region. This gas expulsion can significantly affects the dynamical evolution of subclusters (Goodwin & Bastian 2006). On the other hand, a new generation of stars would be able to form in the gas compressed by feedback from massive stars at the border of an H II region (Elmegreen & Lada 1977; Sandford et al. 1982). Our previous work on the young open cluster NGC 1893 confirmed that a shell of ionized gas surrounding the cluster is expanding from two O-type stars in the cluster center with a velocity of 8.4 km s^{-1} (see the left panel of Figure 1). A pillar-like gas structure is found on the far side of the expanding shell (see the right panel), and several PMS stars in the periphery of the gas pillar are also moving away from the O-type stars with a similar velocity to the gas pillar as shown in the right panel. The kinematic substructure found in this cluster indicates that star formation can be controlled by two different mechanisms, spontaneous and feedback-driven star formation. The fraction of the feedback-driven star formation was estimated to be about 26%, and therefore feedback from massive stars can play an important role in the formation of OB associations (Lim et al. in preparation).

IC 1805 at the heart of the massive SFR W4 is the most massive core cluster in the Cas OB6 association. According to Sung et al. (2016, ApJS, submitted), the cluster is 3.5 million years old, and its total mass is about 2700 $M_{\odot}$. Their member list includes OB stars selected from various photometric diagrams in the optical passbands and a large number of PMS stars identified from Hα photometry, the slope of spectral energy distribution of point sources from the *Spitzer*/IRAC and MIPS photometry, and *Chandra* and XMM-*Newton* X-ray observations (Townsley et al. 2014; Rauw & Nazé 2016). A total of eight O-type stars are concentrated within 8.4 pc from the center of the cluster, and their proper motion is well defined within a narrow range of 2 mas yr^{-1}. On the other hand, B-type stars show a large spread in the proper motion from *Gaia*. An excessive number of B-type stars was found in the mass function of IC 1805. This excess can be seen in the color-magnitude diagram (the left panel of Figure 2). Stars in the magnitude range of 11 – 14 mag show a large spread in luminosity at given colors. The spread is still seen after reddening correction. Also, we do not anticipate that a binary fraction abruptly increases for a specific spectral type. Hence, differential reddening and binarity are unlikely the main factors causing the luminosity spread. The relatively bright B-type stars may be the evolved members of the Cas OB6 association. The central concentration of low-mass PMS stars is not as high as that of high-mass stars, and most of them constitute a halo population as shown in the right panel of Figure 2. Their spatial distribution would be explained by dynamical evaporation by energy equipartition or feedback-driven star formation as seen in NGC 1893. We expect that the stellar population in IC 1805 is composed of three groups formed from different mechanisms, the old member of the Cas OB6 association, the main group of IC 1805, and a new generation of stars as the result of feedback from massive stars. The individual groups may be important building blocks of this OB association.

We propose to measure the RVs of the member stars and ionized gas using a cross-correlation technique and a Gaussian profile fitting method. The kinematic substructure will be searched for in a position-position-velocity diagram, channel maps, and the distribution of the RVs. It is expected that stars within the radius of 8.4 pc from the cluster center have a systemic velocity of the main group, and therefore their velocity component would show a strong peak in the RV distribution. Since a new generation of stars may be formed in a molecular cloud compressed by O-type stars, their RVs would be coincident with those of ionized gas contacting with the cloud. This subgroup would form the secondary peak in the distribution. The other components may be associated with the members of the Cas OB6 association. We will estimate the contributions of individual subgroups to the total stellar population from comparison of the observed RV distribution with results of multiple sets of Monte-Carlo simulations assuming various projection angles to the celestial sphere, the number ratio among the members of the subgroups, observational errors, and binary fractions. The age difference among the subgroups will also be investigated, and the state of dynamical evolution will be inferred from the observed velocity dispersion. We will provide a convincing description of the build-up process of the Cas OB6 association in a time-space-velocity volume. High spectral resolutions of R = 16,000 for stars and 30,000 for ionized gas are empirically required to identify velocity differences larger than 1 km s^{-1}. Our targets are 357 stars with masses larger than 1 $M_\odot$ and 480 positions across ionized gas. The multi-object echelle spectrograph Hectochelle on the 6.5-m MMT is the most suitable instrument to accomplish the scientific goal. The efficiency of observations with Hectochelle/MMT is 2.6 $\times$ N times better than that with 4-m telescopes and 10.5 $\times$ N times better than that with 2-m telescopes, where N is the number of targets.

References

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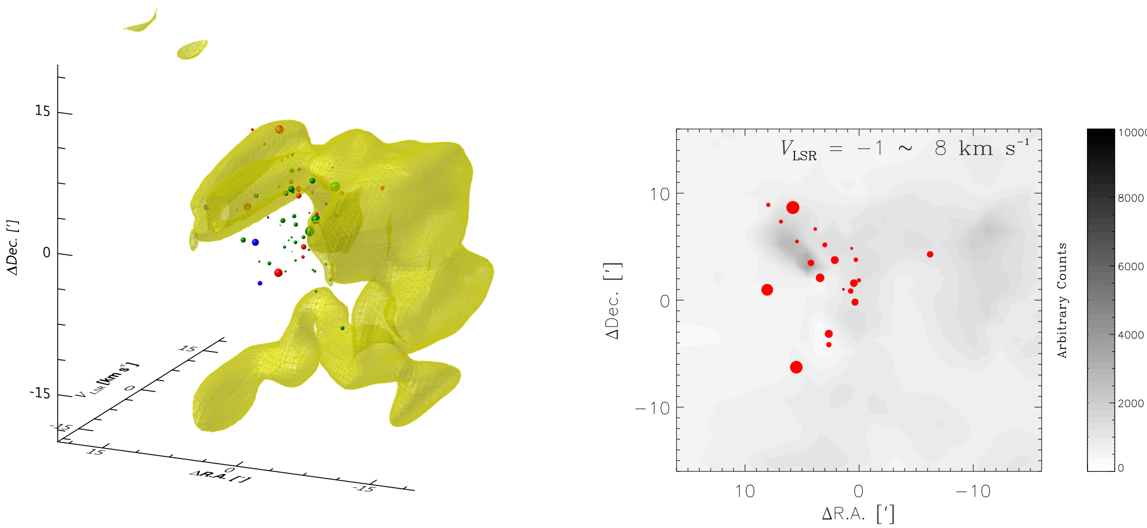

Figure 1: Position-position-velocity diagram (left) and channel map (right) of stars and ionized gas ([N II] $\lambda6584$) in the young open cluster NGC 1893 (Lim et al. in preparation). The position of objects is relative to the O-type star HD 242935 (R.A. = $05^h\ 22^m\ 46.^s5$, Dec. = $+33^\circ\ 25'\ 11''$, J2000). The size of spheres (left) and circles (right) is proportional to the brightness of individual stars. Blue, green, and red colors represent the blueshifted group ($V_{\rm LSR} = -19$ to -10 km s^{-1}), main group with the system velocity ($V_{\rm LSR} = -10$ to -1 km s^{-1}), and redshifted group ($V_{\rm LSR} = -1$ to 8 km s^{-1}), respectively. The channel map shows the kinematic substructure of the redshifted group. Since the age of stars is younger toward the gas pillar ($5'$, $4'$), the formation of stars in the vicinity of the gas pillar is likely to be triggered by feedback from O-type stars in the cluster center ($0'$, $0'$).

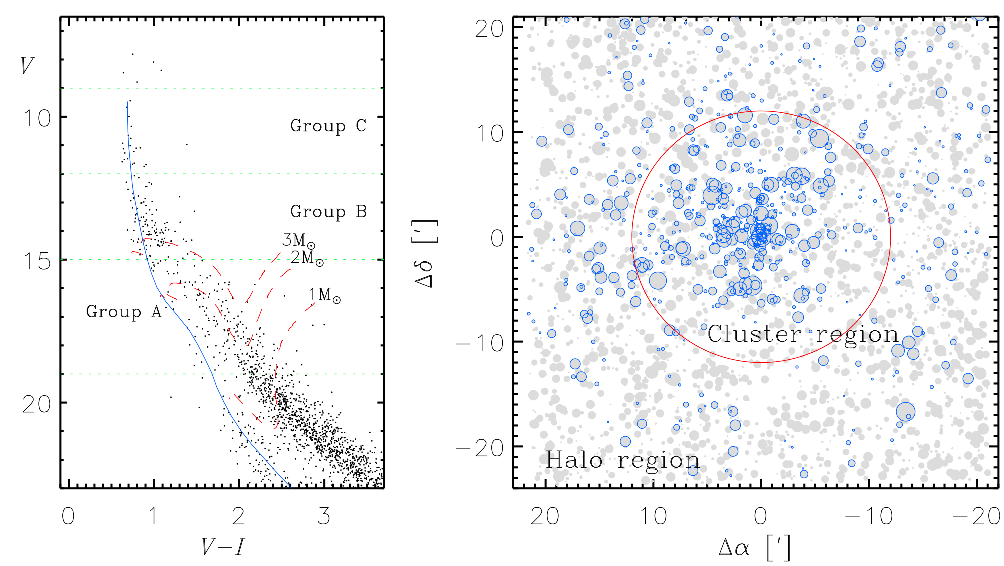

Figure 2: Color-magnitude diagram of member stars in IC 1805 (left) and finder chart of target stars (right). Solid and dashed lines in the left panel are the zero-age main sequence relation (Sung et al. 2013) and the evolutionary tracks of pre-main sequence stars (Siess et al. 2000). Dotted line divides the stars into three groups with a different observing setup. In the right panel, grey dots and blue circles represent all stars within the survey region and target stars, respectively. The size of circles is proportional to the brightness of individual stars.

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**)*

Target Information

The core cluster IC 1805 in a major part of the Cas OB6 association hosts eight massive O-type stars within the central region and a large number of lower-mass stars spreading over our survey region (30 pc $\times$ 31 pc). Feedback from O-type stars creates a cavity in the center of a well-developed H II bubble. Spectroscopic observations of this cluster will provide the best opportunity to constrain the large scale star formation process, i.e. the formation of OB associations, from kinematics. The field of view of Hectochelle (1°) is able to encompass the whole survey region ($43' \times 45'$) in one pointing. The member list was obtained from multi-wavelength observations from X-ray to mid-infrared passbands. We included a total of 357 member stars in the V magnitude range of 9 mag to 19 mag and 480 positions across the ionized gas to the target list.

Observing Condition Constraints

IC 1805 can be observed over an air mass range of 1.2 – 1.6 for 8 hours per night in October and November. The cluster is also observable for 6 hours per night in September and December. Observations can be successfully performed even under bright sky conditions because our targets are point sources and strong emission lines from ionized gas. However, we hope to observe our targets under reasonable seeing conditions better than $1\farcs5$ in order to obtain high signal-to-noise ratios (SNRs).

Observing Setup

We have a plan to use three order separating filters, **RV 31**, **OB37**, and **OB 25**. The prominent Mg b triplet and a large number of other metallic lines will be used to derive cross-correlation functions for A- to K-type PMS stars, and therefore **RV 31** filter (5,150 – 5,300 Å) is the most optimal filter for this purpose. We will measure the RVs of OB stars from the He I λ4387 absorption line using a Gaussian profile fitting method. The cross-correlation technique is inappropriate to measure their RVs because of a small number of metallic lines and of wind effects on hydrogen lines. However, it is known that He I λ4387 provides a reliable radial velocity of OB stars regardless of their luminosity class. **OB 37** filter (4310 – 4400 Å) will be used to observe the absorption line. Interstellar forbidden lines are useful tools to study the tomography of ionized gas because photons emitted from ions are not reabsorbed in the line of sight. The RVs of ionized gas will be measured from the forbidden line [N II] λ6584 using **OB 25** filter (6475 – 6630 Å). Our analysis will be performed on normalized spectra, and therefore additional observations of standard stars for flux calibration are unnecessary. Observations of telluric standard stars are also unnecessary.

We divided the 357 target stars into three groups by brightness and spectral types, **Group A** ($15 < V$ [mag] ≤ 19 for A- to K-type stars), **Group B** ($12 < V$ [mag] ≤ 15 for late-B-type stars), and **Group C** ($9 < V$ [mag] ≤ 12 for O- to early-B stars). **Group D** contains 480 positions across the ionized gas, and two different fiber configurations will be used to observe all the positions (240 fibers $\times$ 2). Observations will be made using a **2 $\times$ 2 binning mode** for the stars to obtain good counts and a **1 $\times$ 1 binning mode** for ionized gas to analyze the line profile of [N II] λ6584 in detail, respectively. In addition, in order to minimize uncertainties due to sky subtraction, in each frame a few tens of fibers will be assigned to blank sky to obtain good sky spectra. These will be median combined to obtain a master sky spectrum with a very high SNR. The usage of such a master sky spectrum suppresses errors arising from subtraction of the sky background.

Exposure times for a single frame for Group A, B, and C are about 45, 20, and 5 minutes, respectively. In order to improve the SNR and to remove cosmic rays, the observation of each group will be repeated three times. The expected SNR for the faintest stars in a given group would be better than 3 (for Group A), 10 (for Group B), and 35 (for Group C) according to the SNRs of spectra previously obtained by the same observing setup. For the Group D, we will also take three frames, where the exposure time of each frame is 20 minutes. A total of 7.2 hours including an overhead of 20 minutes for each group are required to accomplish these observations. However, in previous semesters, the efficiency of fiber allocation of the robot positioners varied between 40 – 80 % (the number of fiber-assigned targets / 240 fibers of Hectochelle $\times$ 100 for each group). Hence, we actually request **a night ($\sim$ 11 hours; Group A $\times$ 2, Group B $\times$ 2, Group C $\times$ 1, and Group D $\times$ 1)** to observe all the targets assuming an efficiency of 65%.

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**)*

These spectroscopic observations of the core cluster IC 1805 in the Cas OB6 association are proposed for the first time to investigate kinematic substructure on a basis of radial velocity measurements. The results from the observations will provide a clue to understanding the build-up process of the Cas OB6 association. We have accumulated rich experiences from a previous study on the young open cluster NGC 1893 (2016A-MMT-1). The kinematic substructure of stars and gas was identified by using a position-position-velocity diagram, channel maps, and the distribution of RVs. The main factor creating such substructure is feedback from massive O-type stars. Hence, we confidently anticipate the success of our new project based on the experiences from the previous study.

A large fraction of the targets (64%) are so faint that observations with small telescopes are definitely inefficient to take the high-resolution spectra of such stars. It is also very difficult to observe a total of 357 targets only using a spectrograph for a single object. Therefore, the Hectochelle on the 6.5-m MMT is the most optimal spectrograph to accomplish the scientific goal of our study. The requested time for the observations is a night ($\sim$11 hours). However, it depends on the weather conditions as well as the stability of the instrument we proposed. If the weather conditions become worse during the observing run, or if the robot positioners malfunction, our observation will not be completed in the allocated nights. That way a few more hours ($\sim$ 5) may be required after this observing run given that typical success rates are between 50 and 75 %.

H.S. has accumulated the spectra of O-type stars in IC 1805 observed with BOES/BOAO in different epochs. The spectra would allow us to check the variations of radial velocities due to orbital motion of stars in binary systems. In addition, J.K. is leading a science project on the same target, but wider area than ours, with the intermediate resolution multi-object spectrograph Hectospec on the MMT. The lower resolution spectra of stars obtained with Hectospec are insufficient to precisely measure the radial velocities of stars, however, the spectra would be very helpful to determine stellar parameters (effective temperature, luminosity, mass, and age) due to its wider spectral coverage.

The Korea Astronomy and Space Science Institute has participated in the Giant Magellan Telescope (GMT) project as a consortium partner (K-GMT Project). The K-GMT Science Group (KGSG) is dedicated to improving the scientific capability of Korean astronomers. As a part of their efforts, KGSG could access 4 – 8 m class optical telescopes and invited Korean researchers to make proposals for observations with the telescopes. The MMT is one of the accessible telescopes. Details on the overview of this program as well as policy can be found in the home pages of K-GMT Science Program[1].

[1] http://kgmtscience.kasi.re.kr/science_program/guideline.html

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)***

A Spectroscopic Study of the Young Open Cluster NGC 2264: A Constraint on the Timescale of Cluster Formation (PI: B. Lim, Co-Is: H. Sung, J. S. Kim, PID: 15A-MMT-001 and 15B-MMT-005) This project was initiated to investigate the timescale of cluster formation using a lithium depletion method for low-mass pre-main sequence stars. Observations with the Hectochelle attached to the 6.5-m MMT were proposed to achieve this scientific goal. We were awarded two half nights during 2015A and 2015B. Our observations were carried out for only 2.5 hours due to bad weather conditions and malfunction of fiber positioner. However, the lithium abundance of 86 pre-main sequence stars in NGC 2264 was successfully derived from the Hectochelle spectra using a curve of growth method. From the lithium abundance, we estimated the formation timescale of NGC 2264 to be 4 – 5 Myr. This result suggests that the extended star formation scenario for young star clusters can be ruled out. A paper on the result has been published in the Astrophysical Journal in November 2016 (ApJ, 831, 116).

A Feedback of High-Mass Stars: Looking for a Direct Evidence for Triggered Star Formation (PI: B. Lim, Co-Is: H. Sung and M. S. Bessell, PID: 16A-MMT-001) This project was proposed to search for direct evidence of triggered star formation in the young open cluster NGC 1893. We were awarded a night during the time block of MMT/Hectochelle in 2016A. A total of eight observing setups were submitted to CfA, and observations for the seven configurations were carried out. The one dimensional spectra of 183 stars and diffuse gas across the cluster were extracted by using IRAF/SPECRED packages. The RV of gas was measured using [N II] λ6584 lines, and that of member stars was obtained using a cross-correlation technique with synthetic spectra. We found that the velocity field of stars in the periphery of the tadpole nebula Sim 130 is coincident with that of expanding gas, rather than that of the central cluster. This result clearly showed the physical causality between feedback of massive stars and the formation of a new generation of stars. We are preparing for a journal paper.

Probe into the Extended Main Sequence Turn-Off of the Galactic Populous Cluster M11 (PI: B. Lim, Co-Is: H. Sung and M. S. Bessell, PID: 17A-MMT-001) The main scientific goal of this project is to figure out the origin of extended main sequence turn-off in the populous clusters. There are two plausible scenarios concerning this issue, age spread scenario and stellar rotation scenario. The rotational velocity of stars at main sequence turn-off in M11 will be measured to test the stellar rotation scenario. We were awarded a night in 2017A, and our observation will be scheduled soon.

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)***