OBSERVING REQUEST
University of Arizona Observatories

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

Characterizing YSOs in the Heart of the Orion Nebula Cluster 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), one of the best and ideal sites to study the effects of external photoevaporation on disk dispersal. We propose to use the MMT/MMIRS multi-object spectrograph to obtain IR spectra ($H\&K$) for 416 young stellar objects (YSOs) in the center of ONC. This program is a necessary complement to an ALMA proposal we are submitting to measure disk masses of YSOs in the same area we propose here (center of ONC near an O star, θ^1C Ori). Optical spectra have been obtained for a number of YSOs in ONC, but not for the central part due to high extinction. Some IR spectra have been obtained ($\sim$30% in the MMIRS field of view), but without accretion measurements. We have selected 416 sources in the MMIRS field of view ($4' \times 7'$) for 9.5<K<15.5mag that were not observed with optical or IR spectroscopy. These targets are the best targets for multi-object IR spectroscopy due to high extinction and high stellar density in ONC. This observation is an important part of the astro-biology program, *Earths in Other Solar Systems (EOS)*, a part of NASAs 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.

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	MMIRS	*		2	grey	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	Field 1	05:35:16.90	−05:25:45.2	K=9.5–10.5, Total Exp=3 minutes
2	Field 2	05:35:16.90	−05:25:45.2	K=9.5–10.5, Total Exp=3 minutes
3	Field 3	05:35:15.20	−05:23:45.1	K=10.5–11.5, Total Exp=5 minutes
4	Field 4	05:35:15.20	−05:23:45.1	K=10.5–11.5, Total Exp=5 minutes
5	Field 5	05:35:15.20	−05:23:45.1	K=10.5–11.5, Total Exp=5 minutes
6	Field 6	05:35:15.20	−05:23:45.1	K=10.5–11.5, Total Exp=5 minutes
7	Field 7	05:35:13.23	−05:23:29.2	K=11.5–12.5, Total Exp=10 minutes
8	Field 8	05:35:13.23	−05:23:29.2	K=11.5–12.5, Total Exp=10 minutes
9	Field 9	05:35:13.23	−05:23:29.2	K=11.5–12.5, Total Exp=10 minutes
10	Field 10	05:35:13.23	−05:23:29.2	K=11.5–12.5, Total Exp=10 minutes
11	Field 11	05:35:13.23	−05:23:29.2	K=11.5–12.5, Total Exp=10 minutes
12	Field 12	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
13	Field 13	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
14	Field 14	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
15	Field 15	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
16	Field 16	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
17	Field 17	05:35:14.28	−05:22:56.0	K=12.5–13.5, Total Exp=20 minutes
18	Field 18	05:35:11.87	−05:21:47.6	K=13.5–14.5, Total Exp=30 minutes
19	Field 19	05:35:11.87	−05:21:47.6	K=13.5–14.5, Total Exp=30 minutes
20	Field 20	05:35:11.87	−05:21:47.6	K=13.5–14.5, Total Exp=30 minutes
21	Field 21	05:35:11.87	−05:21:47.6	K=13.5–14.5, Total Exp=30 minutes
22	Field 22	05:35:11.87	−05:21:47.6	K=13.5–14.5, Total Exp=30 minutes
23	Field 23	05:35:11.19	−05:20:38.8	K=14.5–15.5, Total Exp=30 minutes
24	Field 24	05:35:11.19	−05:20:38.8	K=14.5–15.5, Total Exp=30 minutes
25	Field 25	05:35:11.19	−05:20:38.8	K=14.5–15.5, Total Exp=30 minutes
26	Field 26	05:35:11.19	−05:20:38.8	K=14.5–15.5, Total Exp=30 minutes

Approval for Instrument Use from PI: yes

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

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, 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 stars. External photoevaporation erodes protoplanetary disks outside-in via combination of EUV (hν $\gtrsim$ 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 tentative trend of lower disk mass for objects close to massive stars (e.g. Mann et al. 2015).

We propose infrared spectroscopy of 416 YSOs at the central part of the Orion nebula cluster in immediate vicinity of ionizing sources, a O6 star, $\theta^1 C$Ori 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. This proposed study is intended to characterize sources for which disk masses will be measured with ALMA. Current data can only characterize about 30% of the population in the central part of ONC and without accretion rate estimates. We plan to obtain 416 IR spectra (spectroscopic data) using MMIRS to obtain complete census of YSOs with high extinction. We are proposing to map the central $1.5' \times 1.5'$ of ONC using ALMA in 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.

Why Orion Nebula Cluster?

The Orion nebula cluster (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, $\theta^1 C$ Ori, is the main ionizing source in ONC providing enough UV photons to its environment, and photoevaporating proplyds have been well studied in this region. Therefore ONC is one of the best star forming regions to study photoevaporation of YSO disks in presence of high mass star in their immediate vicinity. 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 to be characterized better using IR spectroscopy, because of high extinction and strong nebulosity**. There have been some infrared spectroscopic data in the region (Slesnick et al. 2004, Ingraham et al. 2014). About 30% of the sources out of total 1009 sources have spectra 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 there work was hampered by a lack of spectral types). We propose to use MMIRS in multi-object mode to obtain H&K band spectra of 416 YSOs in the central ONC, 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. We are submitting an ALMA proposal (PI Eisner) in Cycle 3 to 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

We will obtain IR spectra for 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 here and 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 is older $\sim$4Myr (Bouy et al. 2013).

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; 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; 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; Slesnick et al. 2004, ApJ, 610, 1045; Zsom et al. 2011, A&A, 534, AA73

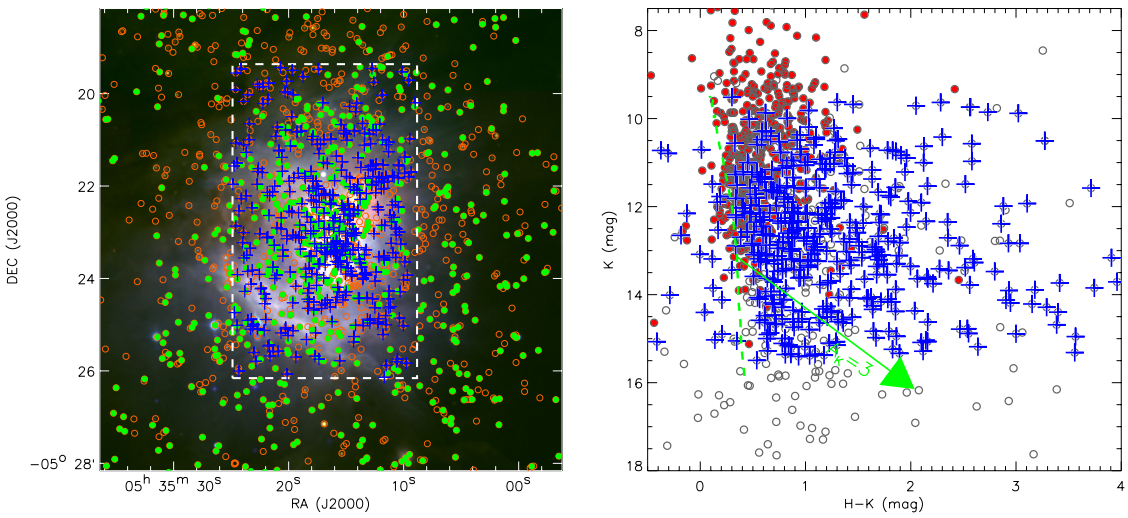

Figure 1: **Left**: Color composite near-infrared (JHK_s) 2MASS image of the central part (the Trapezium Cluster) of the Orion Nebular Cluster. The circles (open and filled) are all the stars in the cluster found by Hillenbrand &Carpenter (2000). The filled circles are the ones which have been observed 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.

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 416 sources. The most ideal instrument for these observations is MMT/MMIRS. We have 416 targets selected for this observation 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$\times 10^{-9}$ 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 cover all the targets we proposed, we need 26 fields. According to the instructions in the MMIRS user manual, we calculated the total needed time as follows: $\sim$25 minutes for the overhead for each field plus integration time (total 18.7 hours). Including on-source exposure, overhead, and calibration, we request a total 2 nights of MMIRS.

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 is the first optical/IR observing proposal for the EOS program.

We are requesting 2 nights of observing run to observe one of the three target fields, ONC. We expect to propose for similar observations for another Orion target, NGC 1977 and another hectochelle observations for NGC 1980 for the 2016A semester.

This optical and IR part of the EOS project is lead by J. Serena Kim and Ilaria Pascucci and a new postdoc, Min Fang, who is to arrive at SO in June, 2015.

We anticipate that the ALMA observations will be executed in Winter 2015. Given the EOS project's timeline the MMT observations should be carried out in the Winter of 2015/Spring 2016 to allow timely publication while funding is available for this project (by Fall 2016). 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**)*

Near-IR Variability Studies of Star Forming Regions: Finding Very Low Mass Young Stellar- and Sub-Stellar Objects (this program-year1). (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. The first look data for just first two epochs for IC 1396A seem successful, however we are still waiting for most of our data to be available in the WSA database.

Accretion, Disk-locking and Kinematics of Young Stars in L1641. (PI: J. S. Kim Co-Is: M. Fang, A. Sicilia-Aguilar, R. van Boekel, T. Henning) Both Hectochelle and Hectospec data were taken during 2010A, 2010C, 2012B. The data have been reduced and analyzed; and one paper is published in ApJS (title: YOUNG STELLAR OBJECTS IN LYNDS 1641: DISKS, ACCRETION, AND STAR FORMATION HISTORY. Fang, Kim, et al. 2013, ApJS. Most recent data have been reduced, and are being analyzed for the next paper. The paper was presented during the IAU stellar astrophysics held in Seoul, Korea in May 2013 (Kim, Fang, et al. 2014).

Accretion variation of Young stars in L1641 J. S. Kim, M. Fang, A. Sicilia-Aguilar, H. Wang, R. van Boekel, T. Henning. The observations have been performed in October-December 2013. The data are reduced and analyzed. One paper is in preparation.

Hectospec Observations of Young Stars in the W3/W4 Star-Forming Regions (PI: J. S. Kim.) A total of 8.67 nights were awarded during the 2008C, 2009A, 2009C, 2010C, 2011C, 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 2012A was unsuccessful due to instrument problem and weather. 0.5 night of DDT time to use the Hectospec was awarded during 2012B. 2.5 more nights were awarded for targets in W4 during 2013A, however the observation was again unsuccessful, because of instrument failure. A 0.5 night was re-assigned during the 2013A at the end of the target visibility window, which was successful. Most of the bright source spectra in W4 data were reduced. All the data in the W3 have been reduced and spectral typing and analysis on high mass stars to intermediate mass stars is on going. 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). Three papers including data from the Hectospec on W3 are in preparation: for high mass stars in the W3 (Kiminki et al.), AFGL333 (Jose, Kim et al.), and for IC 1795 cluster (Kim et al.). Some results on AFGL333 has been presented during the Astrobiology conference held in Tucson, March 2014 (Kim et al.).

UBVI CCD Survey of Open clusters (J. S. Kim, B. Lim, H. Sung). 2010 - 2013. It is a long program to use the Kuiper 61" telescope with Mont4k CCD for our systematic survey of open clusters in the northern hemisphere. The main purpose of the project is to provide the homogeneous photometric data of open clusters. Total 76 targets were observed under photometric night. We have carried out data reduction and photometry for these clusters. Photometry is completed for 22 clusters so far. Data reduction and analysis is on-going. A paper is in preparation, and the project has been presented in a recent meeting (IAU Pacific-Rim Astrophysics conference, May, 2013): Star Formation History in the Bubble Nebula NGC 7635 by Lim, Sung, and Kim (2013). PI Kim is co-advising the graduate student Mr. Lim on this project. Two papers have been published (Lim et al. 2014, MNRAS, Lim et al. 2015 AJ, published)