OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

A final step to complete the spectroscopic survey of young stars in Orion

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Abstract of Scientific Justification

We propose to use the MMT/Hectospec to complete our optical spectroscopic survey of a young stars in the Orion complex. The Orion complex (d$\sim$450 pc) is an excellent site to study the early stages of star formation. The large sample of young stars (1–5 Myr) and their diverse properties of circumstellar disks make this region an ideal site to study disks at various evolutionary stages. It has been surveyed by the Spitzer, WISE, Herschel, XMM, & Chandra, which provided excellent multi-wavelength data for thousands of young stars down to very low masses. Our previous spectroscopic surveys are biased to the disk population. Therefore we will obtain spectra for $\sim$1000 candidate young stars to obtain complete sample of our survey with Hectospec. It is very important to have large sample size to understand the accretion/disk connection in a statistical sense, because individual objects can be very different from each other in both disk and accretion properties. Only by examining large samples we can unveil the physical signs of evolution. With a complete sample of young stars in Orion, we will investigate the star formation history across the Orion complex, and compare it with those of well-studied low-mass star-forming regions. We will construct the initial mass functions (IMF) in various environments, and investigate how the IMF depends on the environments. We will build correlations between local environments/stellar properties and disk properties to investigate influence of these factors on disk evolution. With the Hα and Hβ emission lines we will estimate the accretion rates of individual young stars. We will compare the accretion activity of both the primordial and evolved disks.With such a large sample, we will also re-address the issue on the relation between accretion rates and stellar masses with more statistical significance than before.

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	Hectospec	*		2	grey	Jan–Feb	Jan–Feb	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	Pointing 1	05 41 50.0	-02 10 05	central position of pointing 1
2	Pointing 2	05 41 50.0	-01 35 05	central position of pointing 2
3	Pointing 3	05 47 00.0	+00 22 55	central position of pointing 3
4	Pointing 4	05 35 20.0	-03 10 05	central position of pointing 4
5	Pointing 5	05 35 00.0	-04 10 05	central position of pointing 5
6	Pointing 6	05 37 00.0	-04 10 05	central position of pointing 6
7	Pointing 7	05 35 30.0	-05 00 05	central position of pointing 7
8	Pointing 8	05 35 30.0	-05 30 05	central position of pointing 8
9	Pointing 9	05 35 00.0	-06 20 05	central position of pointing 9
10	Pointing 10	05 35 00.0	-07 05 05	central position of pointing 10
11	Pointing 11	05 35 00.0	-07 50 05	central position of pointing 11
12	Pointing 12	05 35 00.0	-08 30 05	central position of pointing 12
13	Pointing 13	05 41 40.0	-09 13 05	central position of pointing 13
14	Pointing 14	05 43 00.0	-08 30 05	central position of pointing 14
15	Pointing 15	05 41 00.0	-07 45 05	central position of pointing 15
16	Pointing 16	05 38 20.0	-07 00 05	central position of pointing 16
17	Pointing 17	05 44 00.0	-01 00 05	central position of pointing 17

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 for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

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

Scientific Justification

The disk dissipation processes have been investigated by various surveys of large samples of young stars. These surveys probe the inner disk regions using excess emission above the stellar photosphere at infrared wavelengths and find that the lifetime of inner disks is several Myrs (Strom et al. 1989; Haisch et al. 2001; Sicilia-Aguilar et al. 2006; Fang et al. 2013a). Large variety of disk morphologies observed at a given age suggests that the disk evolution is controlled by several parameters: stellar and disk mass, multiplicity, local environments, etc. (Hartmann et al. 2006; Bouwman et al. 2006; Kraus et al. 2012; Fang et al. 2012, 2013a). **Statistically significant samples of young stars under diverse star-forming environments (clustered vs. isolated) and stellar properties (masses and ages) provide keys to understand the dominant parameter for disk evolution.** Spitzer survey programs have shown that a small number of objects seem to be caught in the act of dissipating their disks. These evolved disks can be classified into two types: **radially depleted disks and globally depleted disks** (see Fig. 1). The radially depleted disks show very weak or no excess at near-infrared wavelengths, but strong excess emission at mid-infrared and longer wavelengths, suggesting dust in these disks are cleared "inside out" (Osterloh & Beckwith 1995). The globally depleted disks exhibit uniformly reduced infrared excess compared to primordial disks over all wavelengths out to 24 μm, indicating that there is possibly global dust depletion or grain growth in these disks (Lada et al. 2006; Currie et al. 2009). Investigating these evolved disks will shed light on better understanding of the disk dissipation processes.

The Orion complex is the most active star-forming region in solar neighborhood (see Fig. 1). In this region, two types of star-formation modes (clustered vs. isolated) coexist. In the northern and central part of Orion, the star formation mainly occurs in clusters, e.g. NGC 2024/2068/2071, Orion Nebular Cluster (ONC), and etc., while in the southern part of Orion, where massive stars are absent, and young stars are formed in relative isolation (Fang et al. 2009, 2013b). The Orion complex provides a unique laboratory to investigate disk evolution because (1) there are a large sample of young stars in wide ranges of stellar masses and ages, and (2) the star formation environments vary from the massive clusters (e.g. Orion Nebular Cluster), the medium-size clusters (e.g. NGC 2068/2071), to the distributed population (e.g. L1641), **which provide us a great opportunity to study disk evolution in different environments at a similar distance**. Several projects have been carried out to do optical spectroscopic surveys of young stars toward parts of the Orion complex, including NGC 2068/2071 (Fang et al. 2009), Orion Nebular Cluster (Hillenbrand 1997; Hillenbrand et al. 2013; Fang et al. in preparation), and L1641 (Fang et al. 2009, 2013b; Hsu et al. 2012). During 2007–2013, we have performed spectroscopic surveys of young stars in Orion with VLT/VIMOS and MMT/Hectospec. Partial data from the surveys have been published in Fang et al. (2009, 2013b). **However Our previous spectroscopic surveys are biased to young stars with disks. In addition, in the cluster regions of Orion, e.g. Orion Nebular Cluster, our previous observations preferred the targets at low stellar surface density. Many sources in dense regions are not covered by our previous surveys.** Figure 1 shows locations of young stars without known spectral types. We propose to complete our spectroscopic survey of young stars in Orion with MMT/Hectospec. With the new data from this survey, in combination with the data from our previous surveys and in the literature, our sample will be quite complete to $r \lesssim 19$ mag, corresponding to a 0.2 $M_{\odot}$ pre-main sequence star at an age of 2 Myr and with visual extinction$\sim$2 mag. With the spectroscopic data, together with broad-band photometry in optical and infrared bands, we will address the following questions:

(1) **Characterizing the stellar properties**. The spectroscopic data, in combination with optical photometric data, will be used to derive the stellar properties (masses and ages) by comparing with the pre-main sequence evolutionary tracks. Recently Alves et al. (2012) proposed that there is a large, "old" (4–5 Myr) cluster with negligible extinction extinction in front of Orion A. This "old" stellar population is centered on NGC 1980 and extends to the Orion nebular cluster and L1641, thus contaminate the young stellar populations in the Orion nebular cluster and L1641. However, in Alves et al. (2012) the age of this "old" population is based on two deficient arguments: (1) the age of a massive star, which is runaway star and may be not associated with the NGC 1980 (Hoogerwerf et al. 2000), (2) directly comparing the observed average spectral energy density (SED) of disk population in NGC 1980 to the observed average SEDs of reddened disk populations with known ages without extinction correction. From our proposed observations, in combination of previous surveys, we will obtain the optical spectra of young stars complete to $r \lesssim 19$ mag in the Orion nebular

cluster and nearby regions (NGC 1980/1977,1981). We will characterize the ages of these young stars, thus find out whether the stellar population in NGC 1980 are older than those in the Orion nebular cluster and L1641. Furthermore, with these new data and the data from other spectroscopic surveys (Hillenbrand 1997, Hillenbrand et al. 2013; Fang et al. 2009, 2013b; Hsu et al. 2012, Fang et al. in preparation), we will investigate the global star formation history in the Orion complex for the first time. We will compare the star formation history of Orion with those of well studied low-mass star forming regions, e.g. Taurus. The comparison will provide better understanding of how star formation processes develop in different types of giant molecular clouds. In the Orion star-forming region, Hsu et al (2012, 2013) show the evidence that the initial mass function (IMF) in L1641 is different from that of the Orion nebular cluster. Including the new data from our proposed survey, the samples of young stars with spectral types in Orion will be quite complete to 0.2 $M_\odot$ in Orion. ***We will construct the initial mass functions (IMF) in different regions of Orion, and study how the IMF depends on the local environments ranged from the distributed population (L1641), the medium clusters (e.g. NGC 2068/2071), to the massive clusters (e.g. Orion nebular cluster).***

(2) **Disk evolution.** In our sample, there are a large sample of young stars at various phases of disk evolution in wide ranges of masses, ages, and local environments. Using the infrared data from Spitzer (Megeath et al. 2012), WISE, and Herschel, we will characterize the disk properties of young stars in Orion, e.g. the presence of disks, the evolutionary stages of disks. The previous works in the literature suggest the disk evolution is related to the stellar masses. In isolated star forming regions, e.g. Taurus, Cha I, and etc., disks around intermediate- and solar-mass stars seem to evolve slower than those surrounding the sub-solar mass stars (Luhman et al. 2008, 2010). It seems to be not the case in stellar clusters, e.g. IC 348, PISMIS 24, and etc., where the lifetime of disks around low-mass stars are longer (Lada et al. 2006; Fang et al. 2012). Since the stellar environments vary from distributed populations to massive clusters, our sample can not only allow us to study how the disk evolution is globally related to the local environments, but how the disk dissipation depends on the stellar masses in different environments at the same cloud. Furthermore, with the Hα and Hβ lines on the Hectospec spectra, we can estimate the accretion rates of individual young stars (Herczeg et al. 2008; Fang et al. 2009, 2013b). The comparison of the accretion rates between evolved disk objects and primordial disk population is an important diagnostic to understand the physical mechanism driving the dissipation process (Sicilia-Aguilar et al. 2010). Theoretical calculations predict that the photoevaporation mechanism will become very important in disk dissipation when the accretion rate is lower than the rate of photoevaporative wind (Alexander et al. 2006). Given the large sample of young stars in the Orion complex, we have statistically meaningful number of sample to investigate and compare the accretion properties of young stars at different phases of disk evolution. In literature an empirical correlation has been established between the average accretion rate and the mass of the central star of $\dot{M} \propto M_*^{\alpha}$, with α≈2 (Natta et al. 2006). Recently, it was shown that the slope may be steeper (α≈2.5–3) in the sub-solar mass than for stars of 1 $M_\odot$ or more (α≈1) (Fang et al. 2009, 2013b). Including the new data from our proposed observations and our previous surveys, we will have a large sample of accreting young stars with different ages and at different environments in Orion. With such a large dateset, we can re-address the issue on the relation between accretion rates ($\dot{M}_{acc}$) and stellar masses ($M_\star$) with more statistical significance. Furthermore, we will study how the $\dot{M}_{acc}$ vs. $M_\star$ relation depends on the stellar environments and the ages of young stars.

References

Strom et al. 1989, AJ , 97, 1451 Haisch et al. 2001, ApJ , 553, 153 Sicilia-Aguilar et al. 2006, ApJ , 638, 897 Fang et al. 2013a, A&A , 549, 15 Hartmann et al. 2006, ApJ , 648, 484 Bouwman et al. 2006, ApJ , 653, 57 Kraus et al. 2012, ApJ , 745, 19 Fang et al. 2012, A&A , 539, 119 Osterloh & Beckwith 1995, ApJ , 439, 228 Lada et al. 2006, AJ , 131, 1574 Currie et al. 2009, ApJ , 698, 1 Fang et al. 2009, A&A , 504, 461 Fang et al. 2013b, ApJS , 207, 5 Hillenbrand 1997, AJ , 113, 1733 Hillenbrand et al. 2013, AJ , 146, 85 Hsu et al. 2012, ApJ , 752, 59 Alves &Bouy, 2012, A&A , 547, 97 Hoogerwerf et al. 2000, ApJ , 544, 133 Megeath et al. 2012, AJ , 144, 192 Luhman et al. 2008, ApJ , 675, 1375 Luhman et al. 2010, ApJS , 186, 111 Herczeg et al. 2008, ApJ , 681, 594 Sicilia-Aguilar et al. 2010, ApJ , 710, 597 Alexander et al. 2006, MNRAS , 369, 229 Natta et al. 2006, A&A, 452, 245 Gaustad et al. 2001, PASP , 113, 1326 Getman et al. 2005, ApJS , 160, 319 Watson et al. 2009, A&A , 493, 339 Rebull 2001, AJ , 121, 1676 Carpenter et al. 2001, ApJ , 121, 3160 Rodríguez-Ledesma et al. 2009, A&A , 502 883 Hernández et al. 2004, AJ , 127, 1682

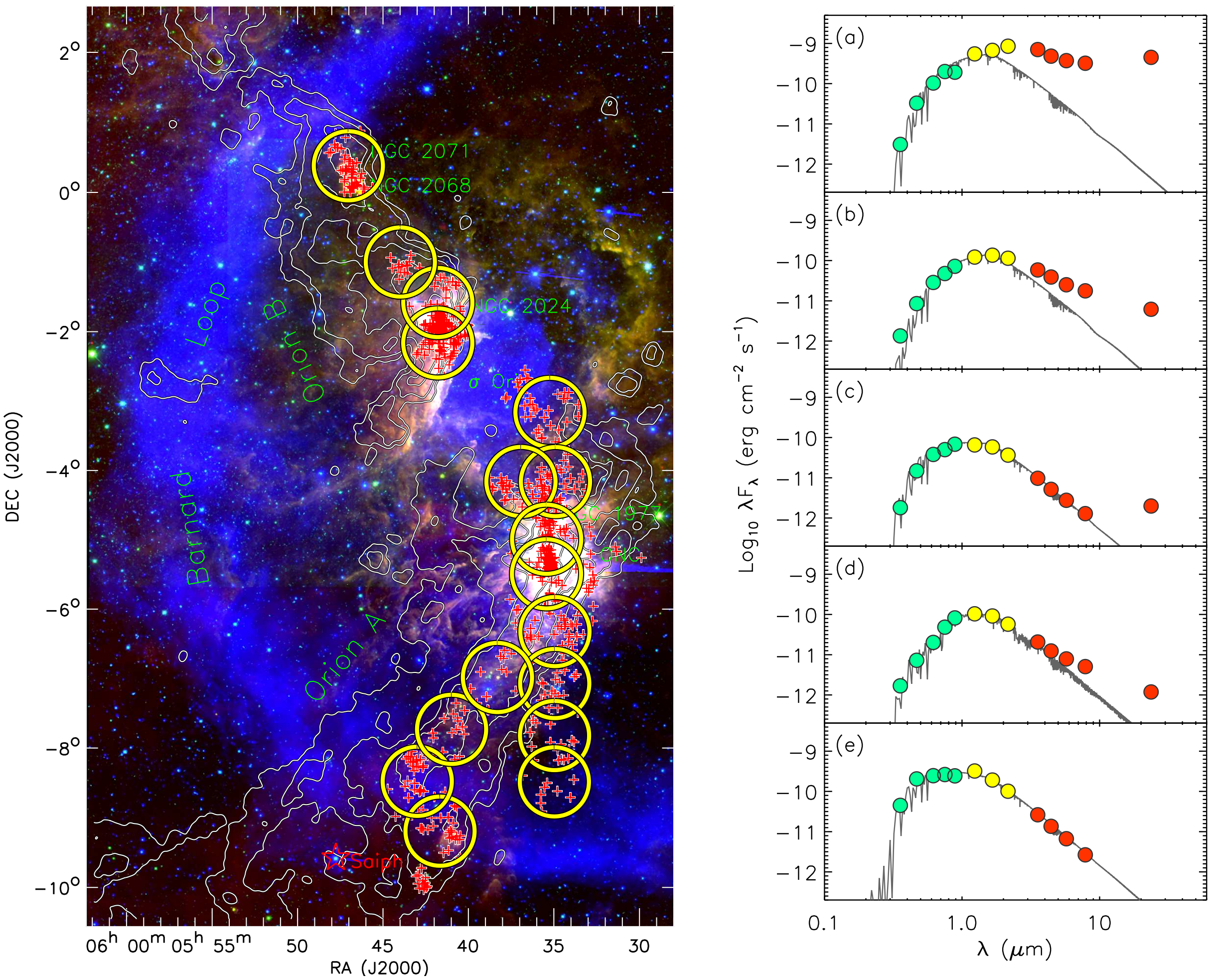

Figure 1: Left: The three-color image of the Orion complex created with the SHASSA image (blue, Southern Hα sky survey atlas, Gaustad et al. 2001), WISE 3.4 micron (green) and WISE 12 micron (red). The contours are the CO map from the Columbia CO survey. The plus symbols are the candidates of young stellar objects (YSO) without spectra with $r \sim 12 - 19$ mag. Proposed fields of spectroscopic observations using the MMT/Hectospec are indicated as yellow circles. Right: Five typical spectral energy densities (SED) of YSO candidates in our sample. From the upper to bottom panels, the disks are at different evolutionary stages: Panel(a,b) for the optically-thick disks, Panel (c) for radially depleted disks, Panel (d) for the globally depleted disk, and Panel (e) for a diskless young star. The photospheric emission level is indicated with a gray curve in each panel.

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)***

The sample of radially depleted disks are selected on having photospheric or slightly redder colors in $K_{\rm s}-[5.8]$, and red colors in $[8.0]-[24]$, suggesting weak or no excess at near-infrared wavelengths, but strong excess emission at mid-infrared wavelengths. In total, we have $\sim$20 radially depleted disk candidates. From the $K_{\rm s}-[5.8]$ vs. $[8.0]-[24]$ color-color diagram, we also propose to obtain $\sim$10 globally depleted disk candidates which show slightly redder colors in both $K_{\rm s}-[5.8]$, and $[8.0]-[24]$. Other young stars are selected using one of the following criteria: (1) showing excess emission in the IRAC $[5.8]-[8.0]$ vs. $[3.6]-[4.5]$ color-color diagram (Fang et al. 2009; Megeath et al. 2012), (2) showing X-ray emission (Getman et al. 2005; Watson et al. 2009), (3) photometric variability (Rebull 2001; Carpenter et al 2001; Rodríguez-Ledesma et al. 2009). With the first criterion, the other young stars with disks can be selected, and with other criteria, both disk and diskless populations can be identified.

We select the targets with r-band magnitude between 12 and 19 mag, and exclude the sources which have been observed with spectroscopy in the literature (Hillenbrand et al. 1997; Fang et al. 2009, 2013b; Fang et al. in preparation; Hsu et al. 2012). In total, we have found $\sim$1000 YSO candidates that meets the above criteria. These sources mainly concentrate on the clusters NGC 2023, 2024, 2068, 2071, 1981, 1977, 1980, and Orion nebular cluster. Here, we propose to perform a spectroscopic survey of the young stars in Orion. Among our sample, $\sim$430 sources are harboring disks at various evolutionary phases, thus provide an excellent sample for studying disk evolution.

The Hectospec mounted on the MMT is the best instrument in the Northern hemisphere for our purposes. With the 300 fibers in one square degree field of view, we can obtain spectra of all our candidates plus numerous sky fibers with just one shoot for each field. Given the magnitude range obtained with the Hectospec, all the candidates in each field can be observed in the same configuration, as we have previously done for star forming regions (L1641, Fang et al. 2013b). We need 17 configurations to observe all the selected targets. For the Hectospec, we will use the 270 gpm grating, which results in spectral coverage of 3650–9200Å. This will give us enough wavelength coverage to do the spectral typing. Combining with optical and near-infrared photometry, we can obtain the bolometric luminosity of young stars, which allows placement of our stars in the HR diagram. Stellar masses and ages can then be estimated by comparison to theoretical pre-main sequence (PMS) evolutionary tracks. From the Hα and Hβ line luminosity, we can estimate the accretion rates using the relation given in Fang et al. (2009).

For the Hectospec, in order to achieve a signal-to-noise ratio (S/N)>10 for the faint targets, we require to obtain 3$\times$10 min science exposures in each one of the clouds. While the S/N in the continuum may be lower for some of the faintest objects (r$\gtrsim$18), most of them are bright enough to provide good S/N in the spectral lines to do the spectral classification according to our experience (Fang et al. 2013b; Fang et al. in preparation).

In addition to the sky fibers assigned together with the science targets, our experience with the Hectospec spectroscopy in star forming regions (L1641, Fang et al. 2013b; the North America and Pelican Nebulae, Fang et al. in preparation; W3/W4 Kim, et al. in preparation) suggests the great advantage of taking an extra set of sky spectra, obtained by offsetting the telescope by a few arc-seconds after the science exposures. This will provide us with a sky spectrum very close to each object. Together with the sky fibers, this will enable us to construct the appropriate nebular spectrum for subtraction, taking into account the different transmission of every fiber and the variability of the nebular emission throughout the clusters. We also request standard bias, flats (taken with our fibers setup) and calibration lamps. The data reduction will be done using IRAF routines (following the same scheme used in our L641 study) together with our own scripts to perform the fiber-to-fiber sky subtraction. We will use the classification scheme developed by Hernández et al. (2004) to perform the spectral typing as we did in Fang et al. (2009, 2013b).

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**)*

In this proposal, we apply for the Hectospec observations at 17 pointings. All our targets have r-band magnitude between 12 and 19. For each field, we need 3×10 min exposures on the targets, and 10 min exposure on the sky. In total, the required time for this proposal is estimated to be $\sim$20 hours, including the exposure time, calibrations, and 30 minutes of overhead for each field.

We have obtained the photometric data sets for all the selected stars from optical to mid-infrared bands, which consist of optical SDSS and Calar Alto/LAICA imaging survey, and infrared 2MASS, Spitzer IRAC/MIPS imaging survey. All these data have been published in Fang et al. (2009). The new data from Hectospec will be combined with the optical and infrared photometry to fully investigate the properties of young stars in Orion.

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)***

⋆*Accretion, Disk-locking and Kinematics of Young Stars in L1641: a Follow-up spectroscopic survey.* J. S. Kim, M. Fang, A. Sicilia-Aguilar, R. van Boekel, T. Henning. The observations have been performed in January 2011. The paper is published (Young Stellar Objects in Lynds 1641: Disks, Accretion, and Star Formation History, 2013, ApJs, 207, 5). The result was presented in a conference in 2013 (Kim, Fang, Siciliar-Aguilar et al. 2014 ASPC, 482, 41).

⋆*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.

⋆*The very low-mass population of the young cluster Tr37.* J. S. Kim, A. Sicilia-Aguilar, T. Henning. Hectospec observations performed in July 2009 and May 2010. The data was reduced, analyzed, and a paper including Hectospec observations, optical photometry and Spitzer/WISE data was published (Sicilia-Aguilar, Kim, Sobolev, et al. 2013. A&A, 559, 3).

UBVI CCD Survey of Open clusters (J. S. Kim, B. Lim, H. Sung). 2010 - 2013. Data reduction and analysis is mostly done. A paper is in preparation, one related paper is submitted to AJ (Lim et al. 2014, AJ, submitted).

Near-IR Variability Studies of Star Forming Regions: Finding Very Low Mass Young Stellar- and Sub-Stellar Objects J. S. Kim, G. Rieke, K. Hodapp, L. Rebull, & J. Stauffer. First two epochs for one of the three fields IC 1396A were observed. Data are being processed at WSA (UK).

LaTeX 2ε UAO Observing Proposal class, 'soprop.cls' v1.3 (2007 Aug 01 [RAJ]).