OBSERVING REQUEST
University of Arizona Observatories

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

A spectroscopic survey of young stars in the Orion's Belt and κ Ori regions of Orion.

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Abstract of Scientific Justification
We propose to use the Hectospec spectrograph on the MMT to continue our optical spectroscopic survey of a carefully selected sample of candidate young stars in the Orion complex. The Orion complex, located $\sim$400 pc distant, is an excellent site to study the early stages of star formation. The large sample of young stars (1–10 Myr) and their diverse properties of circumstellar disks also make this region an ideal site to study disks at various evolutionary stages. In the proposal, we are going to observe two less studied regions in Orion, the Orion's Belt and the κ Ori region. We will obtain low-resolution spectra of these young stars using the Hectospec. We can determine the effective temperatures of these young stars. In combination with the multi-wavelength photometric data and pre-main sequence stellar evolutionary tracks, we can determine the mass, age, and luminosity of each individual star. By combining all the young stars with spectral types in this proposal, from our previous observations and the literature, we will investigate the star formation history across the Orion complex. From the Hα and Hβ emission lines we can estimate the accretion rates of individual young stars. We will characterize the accretion activity of both the primordial and evolved disks in Orion. We will also build correlations between local environments/stellar properties and disk properties, to investigate the influence of these factors 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	Hectospec	*		1.5	grey	Oct-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	Pointing 1	05:42:00	−10:30:00	central position of pointing 1
2	Pointing 2	05:41:11	−09:50:17	central position of pointing 2
3	Pointing 3	05:41:11	−09:06:23	central position of pointing 3
4	Pointing 4	05:37:30	−01:48:29	central position of pointing 4
5	Pointing 5	05:33:05	−02:13:48	central position of pointing 5
6	Pointing 6	05:34:40	−01:39:57	central position of pointing 6
7	Pointing 7	05:35:42	+01:01:03	central position of pointing 7
8	Pointing 8	05:32:06	+00:42:25	central position of pointing 8
9	Pointing 9	05:31:44	+01:21:17	central position of pointing 9

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

Large variety of circumstellar disk morphologies observed by various infrared surveys suggests that disk evolution is controlled by several parameters: stellar and disk mass, multiplicity, local environments, etc. (Hartmann et al. 2006; Bouwman et al. 2006; Fang et al. 2012, 2013). 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. The Orion complex is the best region for such study.

The Orion complex is the most active star-forming region in solar neighborhood. In this region, two types of star-formation modes (clustered vs. isolated) coexist. In the the northern and central part of Orion, the star formation mainly occurs in clusters (e.g. Orion Nebula Cluster), while in the southern part of Orion, where massive stars are absent, and young stars are formed in relative isolation (Fang et al. 2009, 2013). 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 1998, Fang et al. in preparation), and L1641 (Fang et al. 2009, 2013; Hsu et al. 2012). Using these data, a preliminary relation between the disk fractions and ages for various populations in Orion is shown in Fig. 1 (Fang et al. in preparation). In the figure, the disk fractions are estimated using the Spitzer IRAC data, and the ages are derived from Baraffe et al. (1998). We note that the disk fractions smoothly decrease with the ages of the populations in Orion. The typical timescale for disk dissipation in Orion is around 2.6 Myr.

In Orion, there are two regions which are poorly studied. One is the region around the bright star κ Ori (Saiph); the other is the one near the Orion's belt (see Fig. 2). Towards the κ Ori region, Pillitteri et al.(2016) compile a sample of ∼230 young stellar object (YSO) candidates which show X-ray emission or infrared excess emission. However, most of them have not been confirmed with spectroscopy. Furthermore, Pillitteri et al.(2016) argue that the distance of the κ Ori region is 250 pc, and is unrelated with the Orion. A spectroscopic observation of these YSO candidates is important to confirm the distance of this region. If the distance of the region is wrongly treated as 250 pc, but is actually parts of Orion at 400 pc, the isochrone age of this region estimated from H-R diagram will be two time older than its real age. In this case, the the age estimated from its disk fraction using the Fig. 1 is much younger than this isochrone age. This inconsistency could suggest the region should be much more distant than 250 pc. The region around the Orion's belt is parts of Orion OB 1b with an age of 5-10 Myr. Towards this region, Kubiak et al.(2017) provide a sample of 2000 YSO candidates using a set of color-magnitude diagrams. According to our experiences on a spectroscopic survey of YSO candidates in NGC 1980, which are selected using the same method with the one in Kubiak et al.(2017), about 80% of them should be young stars (Fang at al. 2017). In the proposal, we only focus the area with the high surface density of the YSO candidates, and cover 1000 candidates. Thus, we could confirm ∼800 young stars, which will increase the members of Orion OB 1b by a factor of 7. Here, we propose to do spectroscopic surveys of the YSO candidates in the two less studied regions with MMT/Hectospec. With the spectroscopic data, in combination of photometric data from Panstarr, SDSS, Wise, and Spitzer, we can characterize the stellar properties and disk properties of the two regions. The goals of this proposal are described in detail as follows.

(1) **Confirming the youth properties**. We will use the 270 gpm grating, which results in spectral coverage of 3650-9200 Å. The youth of the stars can be characterized using several indicators. The typical one is the Li I absorption line at 6708 Å. The detection of Li I λ6708Å on the Hectospec spectra is a strong indicator of youth property of the object. The strength of the Na I doublets at 8183 and 8195 Å is a good indicator for stellar surface gravity for M-type stars, and can also be used to identify the young stars (Fang et al. 2017).

(2) **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. With these data, we can also investigate the global star formation history in

the Orion complex. Furthermore, in some clusters and sub-regions in Orion, e.g. Orion Nebular Cluster, NGC 2068/2071, Lynds 1641, and etc., the samples of young stars with spectral types in our work in combination with the data in the literature, will be quite complete to SDSS $r' \lesssim 19$ mag. With these data, we will also study how the initial mass function depends on the environments.

(3) **Disk evolution.** In Orion, there are a large sample of young stars at various phases of disk evolution in wide ranges of masses, ages, and local environments. By relating the disk properties to stellar properties and local environments, we can study which factor dominates disk evolution. 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). 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 disk wind (Alexander et al. 2006). Given the large sample of young stars in the Orion complex, we can investigate and compare the accretion properties of young stars at different phases of disk evolution.

References

Hartmann et al. 2006, ApJ , 648, 484 Bouwman et al. 2006, ApJ , 653, 57 Fang et al. 2012, A&A , 539, 119 Fang et al. 2013, A&A , 549, 15 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. 2013, accepted by ApJS Hsu et al. 2012, ApJ , 752, 59 Hillenbrand 1997, AJ , 113, 1733 Megeath et al. 2012, AJ , 144, 192 Herczeg et al. 2008, ApJ , 681, 594 Sicilia-Aguilar et al. 2010, ApJ , 710, 597 Alexander et al. 2006, MNRAS , 369, 229 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 Fang et al. 2017,AJ , in press

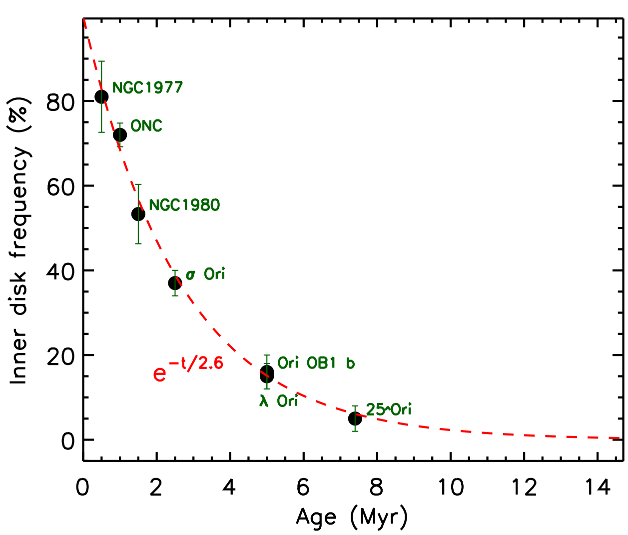

Figure 1: Disk frequencies for different clusters in Orion plotted as a function of their ages

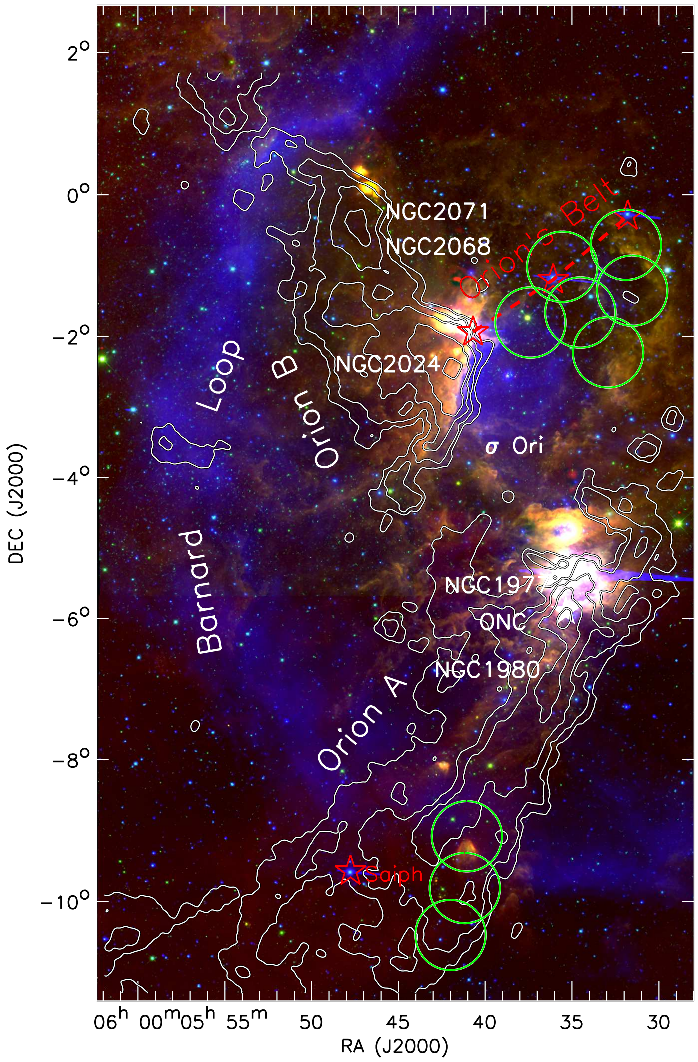

Figure 2: The three-color image of the Orion complex created with the SHASSA image (blue, Southern Hα sky survey atlas, Gaustad et al. 2001), WISE 3.4 micron (green) and WISE 12 micron (red). The contours are the CO map from the Columbia CO survey. Proposed fields of spectroscopic observations using the MMT/Hectospec are indicated as green circles.

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 plan to acquire optical spectra of the candidate members in two less studied regions in Orion, the κ Ori region and the Orion's Belt. The targets are selected from Pillitteri et al. (2016) and Kubiak et al. (2017), and show r-band magnitude between 13 and 19.5 mag. In total, we have found $\sim$1200 targets which are distributed in nine fields. In Fig. 2, we show the planned fields for MMT/Hectospec.

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 other regions (L1641 and NGC 1980, Fang et al. 2013b, 2017). We need 9 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 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$15 min science exposures in each one of the fields. While the S/N in the continuum may be lower for some of the faintest objects (r$\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, 2017).

In addition to the sky fibers assigned together with the science targets, our experience with the Hectospec spectroscopy in star forming regions (L1641 and NGC 1980, Fang et al. 2013b, 2017) 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 L1641 and NGC 1980 study) together with our own scripts to perform the fiber-to-fiber sky subtraction. We will use the classification scheme developed by us to perform the spectral typing (Fang et al. 2017).

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 9 pointings. All our targets have r-band magnitude between 13 and 19.5. For each field, we need 3×15 min exposures on the targets, and 15 min exposure on the sky. In total, the required time for this proposal is estimated to be $\sim$13.5 hours, including the exposure time, calibrations, and 30 minutes of overhead for each field.

We have the photometric data sets for all the selected stars from optical to mid-infrared bands from Panstarr, SDSS, Wise and Spitzer. The new data from Hectospec will be combined with the optical and infrared photometry to fully investigate the properties of these candidate members in the two less studied regions.

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**)*

Spectroscopic Studies of Triggered Star Forming Region IC 1396: Membership and Kinematics J. S. Kim,A. Sicilia-Aguilar, K. V. Getman, M. Fang. The observations have been carried out in May 2014. The data are reduced and analyzed. A paper is in preparation.

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

⋆ *Characterizing YSOs in the Heart of the Orion Nebula Cluster using MMT/MMIRS multi-object spectroscopy,* J. S. Kim, I. Pascucci, M. Fang, J. Eisner, D. Apai, L. Allen

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**)*