OBSERVING REQUEST
University of Arizona Observatories

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

The Spectroscopic Initial Mass Function of a Young Star Cluster that Just Evolved from its Parental Cloud (II)

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Abstract of Scientific Justification

We propose to use Hectospec to obtain spectra of 354 photometric candidates to members of the ≈ 7 Myr old 25 Orionis group (25 Ori) with estimated masses in the range $0.06 < M/M_\odot < 1$ as part of an ongoing project to obtain the spectroscopic IMF in the complete mass range of 25 Ori ($0.01 < M/M_\odot < 10$). These observations will allow us: (i) To confirm the membership of ≈ 270 candidates using spectral features sensitive to youth and surface gravity. (ii) To distinguish the 25 Ori members from those belonging to other populations within the Orion complex, through their distributions in H-R diagrams. (iii) To determine, together with available data, *the IMF of 25 Ori with a 99% complete sample of spectroscopically confirmed members in the mass range* $0.06 < M/M_\odot < 10$, covering the expected peak of the IMF as well as part of the sub-stellar mass domain. (iv) To compare the resulting IMF against those from other stellar groups inside the Orion complex. The 25 Ori group shows several advantages: at its age the accretion and dissipation of circumstellar material around most stars are expected to be ended and the dynamical disruption effects can be avoided, it spans a relative small area ($\approx 3\ \mathrm{deg}^2$), is close to the Sun ($\approx$ 330 pc) and shows very low extinction ($A_V \approx 0.3$ mag). These properties, together with the completeness and quality of our candidates, make 25 Ori the ideal place for a robust determination of the IMF and Hectospec is the ideal instrument for this study because its sensitivity and spatial coverage. We emphasize that the only IMF estimation for 25 Ori so far came from a sample of photometric candidates in the mass range $0.03 < M/M_\odot < 0.8$ (Downes et al. 2014) and that most spectroscopic studies in other stellar groups have determined the IMF as an expectation as they are based on incomplete samples.

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			1.0	grey	Nov–Dec	Oct–Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

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-2017B-a	81.4	1.35	OB association, 77 new YSO candidates
2	Field-2017B-b	80.9	2.14	OB association, 67 new YSO candidates
3	Field-2017B-c	81.7	2.2	OB association, 82 new YSO candidates
4	Field-2017B-d	80.7	1.35	OB association, 59 new YSO candidates
5	Field-2017B-e	82.2	1.55	OB association, 69 new YSO candidates

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
Genaro Suárez	Carlos Román-Zúñiga		no	yes

Scientific Justification

The Initial Mass Function (IMF) of stellar populations is one of the crucial inputs in astrophysics, forming a connecting thread from the process of star formation to the evolution of galaxies. However, because of most IMF studies are based on photometric and/or incomplete spectroscopic samples and the several uncertainties related with the estimation of stellar masses, there are large uncertainties, particularly in the sub-stellar and low-mass star domains that lead to important discrepancies in literature (e.g. Bastian et al. 2010).

We have the goal of constructing a spectroscopic-based system-IMF from a statistically complete sample in the complete stellar mass range. We propose to get this sample from the 25 Ori group (e.g. Briceño et al 2005, 2007 [B05,B07], Downes et al 2014, 2015 [D14,D15]), a stellar group that may be ideal, as it is young enough to still keep all its members but old enough that most of its members have already attained their final masses and also shows several observational advantages.

The critical age for most clusters is close to 10 Myr, as they enter the so called *Fossil Star Forming Region* phase, when most of the gas is removed, the fraction of young stellar and sub-stellar objects with accretion disks is diminished, and both the initial conditions and the age spread effects are minimized with respect to the embedded phase (Walter et al. 2008). The Orion B complex contains young stellar populations near this critical age in its westernmost OB1a sub-association. Within this region, the 25 Ori group harbors ≈ 300 confirmed members with masses in the range $0.01 < M/M_{\odot} < 10$, with an age of $\approx$ 7 Myr and at a distance of $\approx$ 330 pc (B05,B07,D14,D15). The 25 Ori group is one of the most populous groups at this age within 500 pc from the Sun.

An important observational advantage of 25 Ori is that its extinction is very low ($A_V \approx 0.3$), which allow us to observe even their least massive members down to planetary masses (D15). As the accretion disk in 25 Ori is almost over (Hernández et al 2007, [H07]), most of the members have attained their final masses, and also, the most massive members have not evolved off the main sequence (MS) yet. These conditions assure that the 25 Ori IMF constructed with pre-MS members is very close to the IMF defined with MS stars.

Using optical wide-field synoptic photometry from the CIDA Variability Survey of Orion (Briceño et al. 2001) and deep photometry from the CIDA Deep Survey of Orion (D14) as well as IR observations from VISTA, 2MASS, and IRAC and MIPS data from the Spitzer Space Telescope, we have identified and characterized a large fraction of the stellar populations spread across the Orion OB1a sub-association down to the very low mass and the sub-stellar mass regimes (B05, B07, H07, D08, D14, D15, Suárez et al. 2017 [S17]) particularly in 25 Ori. The left panel of Figure 1 shows the selection of photometric candidates according to their position in color-magnitude diagrams that includes optic and near-IR photometry which separate the 25 Ori members from the field stars with an efficiency of $\approx 85\%$ (D14). Our results gave relevant information on fundamental issues about the characteristic time in the evolution of circumstellar disks, the spatial distribution of stars, and how these properties depend on the stellar mass. Also, we gave the first estimation of the IMF for 25 Ori and its surroundings in Orion OB1a.

Although we have an excellent sample of photometric candidates, the spectroscopic follow up is essential to such studies. Only with spectroscopy we can confirm the membership and determine spectral types, extinctions and effective temperatures. Our ongoing spectroscopic survey of 25 Ori covers several mass ranges using different facilities:

(i) The high mass regime (2.0 $M_{\odot}$ to 10.0 $M_{\odot}$) was surveyed with single slit Echelle spectroscopy using the 2.1m telescope at San Pedro Mártir Observatory (SPMO) from winter 2014 to winter 2016. We have already observed the 100% of the candidates.

(ii) For the solar mass and high mass regimes (0.4 $M_{\odot}$ to 6.0 $M_{\odot}$) two high priority plates to observe 25 Ori using the SDSS-IV/APOGEE-2 high-res IR spectrograph were assigned. All the visits for these plates have already been completed during the last semester. These spectra are providing additional information on radial velocities and chemical abundances which will complement the characterization of the group by adding 3D dynamic information and possible chemical gradients within the Orion complex.

(iii) In the low and very low mass stars regimes ($0.07M_{\odot}$ to $0.9M_{\odot}$) most of our observations were performed using Hectospec and FAST at SAO. B05 confirmed $\approx$ 30 LMS members using FAST. B07 studied the kinematics of ≈ 50 members of 25 Ori using Hectochelle and Hectospec and D08 and D14 found ≈80 LMS in 25 Ori using Hectospec. Recently S17 found ≈50 additional LMS using public data from the BOSS/SDSS-III survey.

(iv) In the sub-stellar mass domain ($0.01 < M/M_{\odot} < 0.07$), D08 reported the confirmation of the first sub-stellar members of Orion OB1a from Hectospec observations and D15 reported 15 new brown dwarfs including the least massive members of 25 Ori found so far ($\approx 0.01 M_{\odot}$) using GTC/OSIRIS. The survey of the sub-stellar population is ongoing and we have confirmed 15 additional low-mass brown dwarfs with GTC/OSIRIS during 2016 and 2017 (Downs et al in prep). These spectra represent the 70% of the expected members in the mass range $M < 0.02$ $M_{\odot}$.

Even so, one more push of observational work is needed in order to complete the spectroscopic survey of all the targets that still remains as photometric candidates to members of 25 Ori. Particularly, more observations are needed in the LMS, VLMS and sub-stellar domains with spectral classes between M1 and M7, where the majority of the members are found. We propose to use Hectospec to complete the spectroscopic follow ups in these stellar mass ranges by the observation of the remaining 354 candidates.

The region contains 964 candidates members in this spectral type range of which 607 ($\approx 60\%$) were already confirmed as members in previous studies. Particularly, we obtained Hectospec spectra for 400 candidates during 2016B. These targets span 5.7 sq. deg. in the Orion OB1a area including the 25 Ori group.

In terms of the spatial coverage, these proposed observations, together with previously obtained data, will provide a 99% complete sample within the currently estimated extent of 25 Ori ($1.0\deg$ *radius) and a 92% complete sample in the surrounding OB1a area.* This spatial coverage is important in order to distinguish 25 Ori from other surrounding groups such as ASCC18 and ASSC20 (Kharchenko et al. 2013). The observations proposed here will result in one of the very few spectroscopic studies of the IMF covering the complete stellar mass range (e.g. Hillenbrand et al. 2013). Most IMF studies are based on very incomplete samples due to high extinction and/or far distance, therefore our proposed observations will provide a valuable dataset to study the IMF down to very low mass objects on basis of spectroscopically confirmed members. The final statistical completeness of the IMF sample will be strictly tested using Bayesian techniques and a formal probabilistic scheme proposed by Cerviño et al. (2013).

References:

Bastian et al. 2010, ARA&A, 48, 339
Briceño et al. 2005, AJ, 129, 907
Briceño et al. 2007, ApJ, 661, 1119
Cerviño et al. 2013, A&A, 553, A32
Downes et al., 2008, AJ, 136, 51
Downes et al. 2014, MNRAS, 444, 1783
Downes et al. 2015, MNRAS, 450, 3490
Fang et al. 2013, ApJ, 207, 5
Hernández et al., 2007, ApJ, 671, 784
Hillenbrand et al. 2013, AJ 146, 85
Jose et al. 2015, ApJ submitted
Kharchenko et al. 2013, A&A 558, A53
Suárez et al. 2017, accepted for publication in AJ
Walter, F. M. et al. 2008, in Proc. of the 15th Cool Stars Workshop.

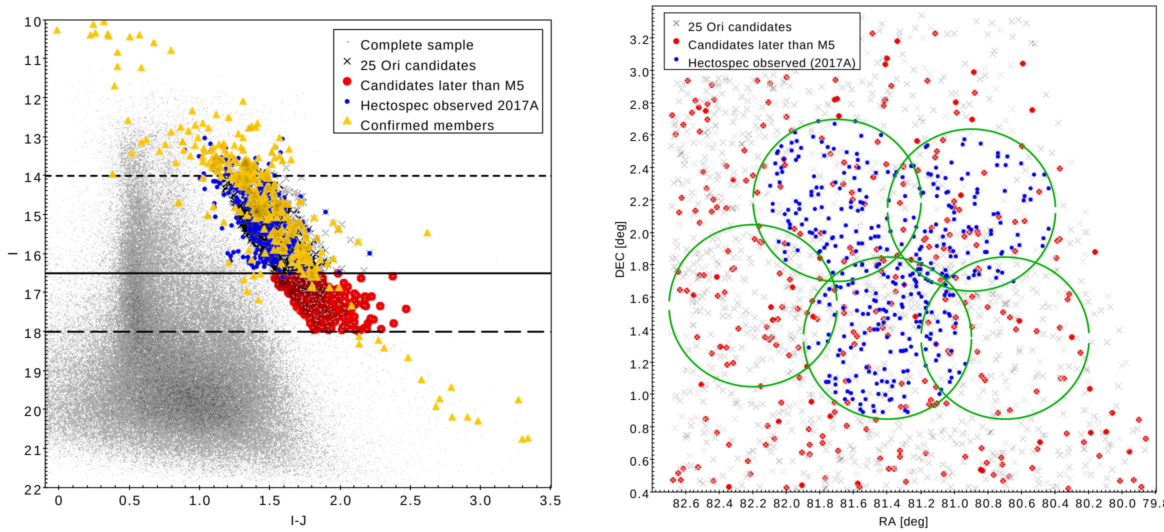

Figure 1: **Left:** I vs I-J color-magnitude diagram of point sources detected in the area covered by 25 Ori (gray points), photometric candidates (gray crosses), low-mass stars observed with Hectospec and confirmed as members during 2016B (blue dots) and the sub-stellar candidates proposed as part of the requested 2017B observations (red dots). The orange triangles indicate the members spectroscopically confirmed so far. Upper and lower dashed lines indicate the I brightness range of the proposed observations and the horizontal solid line indicates the I-band brightness of the sub-stellar mass limit for 25 Ori. **Right:** Spatial distribution of photometric candidates. Symbols are as in the left panel. The green circles indicates the 5 Hectospec fields to be covered for this proposal.

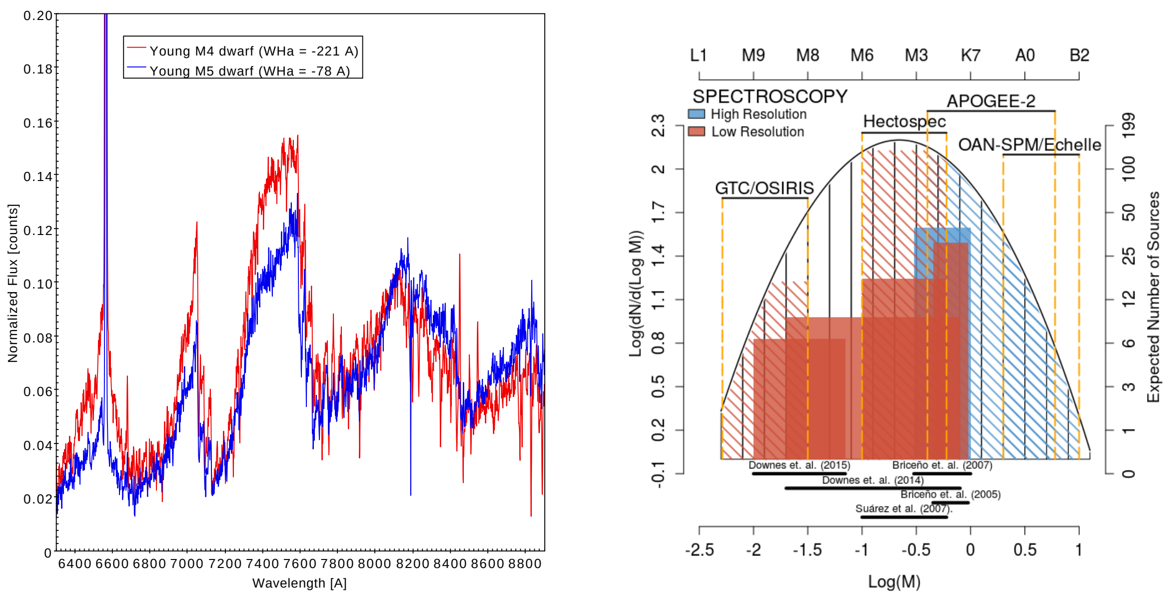

Figure 2: **Left:** Examples of M young dwarfs confirmed as members of 25 Ori from our Hectospec observations during 2016B. Both sources show strong Hα (6563$\AA$) emission indicative of ongoing magnetospheric accretion. **Right:** Completeness of our spectroscopic survey of 25 Ori. The solid line indicates the IMF reported by D14 obtained from photometric candidates in the mass range $0.03 < M/M_{\odot} < 0.8$ and its extrapolation for lower and larger masses. The colored histograms indicates the completeness of the spectroscopic observations obtained with several facilities for different mass ranges.

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 main goal of the proposed observation is to confirm the memberships of photometric candidates with estimated spectral types between M1 and M7. With this confirmation we can estimate the extinction and plot the members in the H-R diagram from which the mass and age can be determined by comparison with theoretical isochrones and evolutionary tracks. Our photometric selection was done using a carefully defined sequence for members of Orion OB1a and 25 Ori in optic-IR color-magnitude diagrams providing an excellent color leverage to separate members from the field dwarf and the extragalactic sources as shown in left panel of Figure 1. As 25 Ori is away from the galactic plane ($b \approx 19$ degrees), the contamination by field stars is low, so we have a global efficiency of ≈85% in our candidate sample as shown in D14,D15.

The spectral type range we expect to cover runs from M1 to M7 with a brightness range $14 < I/mag < 18$. 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 classification following the schemes from Hernández et al. (2006), Fang et al. (2013) and Hillenbrand et al. (2013). The Hectospec wavelength range will permit to classify them successfully using metal oxide bands, such as TiO (e.g. λ6760, λ7100 Å) and VO (e.g. $\lambda 7445$, $\lambda 7865$ Å). To confirm the membership of the candidates we will rely on youth signatures such as Li$\lambda 6708$ in absorption and Hα in emission, and low-surface gravity indicators such as the NaI$\lambda 8183, 8195$ doublet in absorption. When available, we will also use proper motions, X-ray counterpart emission and IR excesses from circumstellar emission.

We propose to observe 5 Hectospec fields that make an almost complete spatial coverage in a roughly circular area of approximately 1.35 degrees radius in the Orion OB1a sub-association, centered in the 25 Ori group as shown in the right panel of Figure 1. Inside this area we have a total of 964 candidates out of which 607 have been observed in previous works as shown in Figure 2. *The observations we propose here will allow to observe the remaining 354 candidates, for a completeness of 99% in the considered spectral type range after removing duplicates and fiber collision conflicts.* Each of the 5 fields we propose to observe will contain between 59 and 82 candidates. We will also use ≈ 30 sky fibers for each field.

The Hectospec ETC indicates that we can reach a $S/N > 30$ for the faintest objects in 6×15.0 minute integrations. We will need 5 to 10 minutes for each fiber reconfiguration. Overhead such as calibrations and setup for each field, we would need a total of 8.3 hours of telescope time. This Orion field can be observed during 2 half-night after mid November. Since the Hectospec runs are scheduled using queue mode, our targets can be observed during second half of the nights after mid October.

For data reduction we will use the *HSRED* IDL reduction package and/or the IRAF Hectospec reduction routines to remove bias and darks, to make normalized dome flats, to extract individual spectra, calibrate in wavelength and subtract the sky background. We expect that the very low extinction toward 25 Ori assures negligible problems with this last step.

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**)*

We are asking for 8.3 hours to observe 5 Hectospec fields. In our previous Hectospec run during 2016B we completed only 60% of our observing goals. In this proposal we request observation time in order to complete the 2016B run and also extend our observations below the sub-stellar mass limit.

The proposed project is currently related to observations of the OB1a region above the solar mass range using single-slit Echelle observations using the 2.1m telescope at San Pedro Martir, and with a successful campaign of observations (2012-2017) in the sub-stellar regime using single-slit spectroscopy with OSIRIS at the GTC 10m in Spain (D15, Downes et al. in prep.), observations with the APOGEE-2/SDSS spectrograph and previous runs with Hectospec.

The synergy between UNAM and UA towards the project of the future 6.5 San Pedro Martir telescope could be certainly reinforced by projects like this. In some of the proposed science cases from UNAM, we already proposed the possibility of having the Hectospec-Hectochelle system as a guest instrument in the 6.5m to perform this kind of science.

Walter and Kim are collaborating on studying very low mass objects in Orion OB1a and b using DECam data in g, r, i, z, and Y band (limiting magnitude of the survey at g band is about 26th magnitudes). As Suárez as PI, we also have deep i band observations using DECam data centering roughly in 25 Ori to complement the CIDA Deep Survey of Orion (D14) catalog in order to construct the photometric-based IMF with a complete photometric sample.

This project is closely related to a survey of the Orion complex by the Young Star and Young Cluster working group within the Science Goal Projects of the SDSSIV-APOGEE-2 collaboration. Kim, Fang, Suárez, Román-Zúñiga, and Downes all are members of this working group. The APOGEE-2 observations will be a strong addition to previous studies led by Kim and Fang in the Orion region using MMT and other spectrometers in other regions of Orion. The observations we propose will provide a valuable sample to study star forming history of the Orion region by adding the 5-10 Myr old OB1a and 25 Ori to the most studied younger regions of Orion (e.g. ONC, NGC 2024, NGC 1977, L1641; 1-2 Myr, OB1b and σOri ; 3-5 Myr).

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**)*

⋆ *The Spectroscopic Initial Mass Function of a Young Star Cluster that Just Evolved from its Parental Cloud* (PI J. S. Kim with members of the SDSS IV, APOGEE-YSO team) We were awarded 1 night to use Hectospec for YSO targets in 25 Ori. Two fields of the data were taken, yet only 60% of the observations were carried out. The obtained data were reduced, and are being analyzed. Spectral typing has been carried out.

Characterizing YSOs in the Heart of the Orion Nebula Cluster using MMT/MMIRS multi-object spectroscopy (PI: J. S. Kim, Co-Is: M. Fang (SO), I. Pascucci (LPL), J. Eisner (SO), D. Apai (SO/LPL), L. Allen (NOAO)). One night of MMIRS time was awarded in 2015B and 2 nights in 2016A from December 31, 2015 to January 2, 2016. For our 2016A run, masks could not be made due to holiday schedule, therefore we used MMIRS in ingle slit spectroscopy mode. We were awarded 2017A run to complete the proposed MMIRS observations, but bad weather condition left about 180 sources that we planned, with for 2017A runs. We have published part of the data for the lowest mass proplyd found in ONC from this dataset (Fang et al. 2016, ApJL, 833, 16). The ALMA Cycle 2 paper on ONC has been published (*J. Eisner et al. 2017, ApJ, 826, 16*), and our team is analyzing the recently obtained ALMA data.

Near-IR Variability Studies of Star Forming Regions: Finding Very Low Mass Young Stellar- and Sub-Stellar Objects (Year1 (2014) is completed, and Year 2 (2015) observations were carried out only for 20%. For Year 3 (2016), we only obtained 10 epoch data for IC 1396A). (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 for all regions (IC 1396A, NGC 1977 NGC 1980). Only small portion of data were obtained for year 2 (2 epoch only) The first look data for for most of the observations during year 1 was successful. Few images for Orion show trailing problem. For most complete data set was taken for IC 1396A, we are analyzing the UKIRT data, and a paper is in preparation (Meng et al. in prep.).

Near-IR spectroscopic survey of young stars associated with the feedback driven star forming region AFGL333 in W3 complex (PI: J. S. Kim, Co-Is: Jessy Jose, Greg Herczeg) In 2017A, we were awarded 1 night (bright) to use MMT/MMIRS for this project. Due to bad weather condition, we obtained about 30% of the proposed data. The data reduction and spectral extraction was done and the data are being checked for telluric correction, etc. The S/N of some of the objects were too low due to cloudy observing condition.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

This project is related to a Ph.D. thesis project who is working with the PI and the SDSS IV APOGEE2-YSO team. It is time critical to obtain this data before our APOGEE data become public, and for the student to graduate on time.