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

Mass Ratios & Masses of Young Spectroscopic Binaries in Orion

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Abstract of Scientific Justification

Mass is the most fundamental stellar parameter. Most stars live in binary systems. Mass ratios of binaries are key to our understanding of binary formation, binary component evolution, and the potential for and character of circumbinary planet formation. To anchor models of pre-main sequence stellar evolution to precise observations, a statistically significant sample of pre-main sequence binary mass ratios is needed. With photocenter orbits from GAIA observations within the next year or two, the combination of mass ratios and inclinations will yield an unprecedentedly large number of young star absolute masses. To this end, we propose to obtain two more epochs of radial velocity measurements on a sample of about 100 candidate spectroscopic binaries in the Orion star forming region.

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	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	Orion Nebula Cluster	05:34:00	−05:30:00	Cluster

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
Larissa Nofi	Lisa Prato		no	no

Scientific Justification

Absolute masses of T Tauri stars lay the foundation for the astrophysics of low-mass star formation. Once composition is established, a star's mass determines all subsequent properties and the very nature of its life and death. Stellar mass dictates the environment for planet formation and the suitability for, and sustainability of, potential life on exoplanets. The traditional approach to identifying young (1 to a few Myr) star masses has been to estimate the stellar luminosity and effective temperature and to map these quantities onto the Hertzsprung-Russell (H-R) diagram in comparison with models of star formation and evolution (e.g., Weinberger et al. 2013). However, models for low-mass stars suffer from the lack of a reliable observational framework and incomplete knowledge of molecular opacities, and diverge on choice of equation of state and somewhat arbitrary initial conditions (Baraffe et al. 2015). Simon (2008) illustrated the discrepancies between five sets of low-mass tracks (Figure 1). Only one to two dozen young star masses are known to better than 5%. **We propose to (1) determine the young spectroscopic binary mass ratio distribution for $\sim$100 systems in Orion which will provide unprecedented insight into close binary formation mechanisms, currently poorly understood, and (2) obtain masses for the component stars in these Orion pairs in order to anchor pre-main sequence evolutionary models to precise observations, necessary to determine of properties such as the initial mass function and star formation history in young clusters.**

Dynamically measured mass ratios number $\sim$4 dozen from a heterogeneous sample of star forming regions (Figure 2). Most stars in the Solar neighborhood reside in binary or multiple systems, but we do not yet have a satisfactory picture of how they form, especially the shortest period systems. Theory has reached a point where simulations of entire clusters of young stars yield mass ratio distributions for sub-samples of various primary star mass; the SPH code of Bate (2012) yielded concrete outcomes which are possible to test observationally. Unfortunately, there are no samples of homogeneous young star mass ratio distributions of any significant size for comparison. The systems shown in Figure 2 are culled from several different investigations, vary in precision from a few to a few tens of percent, and include an assortment of results from half a dozen star forming regions with ages $1-25$ Myr. There are no data for a homogenous mass ratio distribution in Orion or for any other star forming region.

We propose to spectroscopically determine mass ratios in a sample of $\sim$100 pre-main sequence (PMS) spectroscopic binaries in the Orion Nebula Cluster (ONC) with initial identifications (Tobin et al. 2009, 2013; Kounkel et al. 2016). Although these systems are angularly unresolvable with current ground-based technologies, high-precision astrometry such as that being carried out by the GAIA all-sky mission, will provide the visual orbit parameters required to determine absolute masses for all the individual stars in our target binaries with the completion of the GAIA mission; a partial tally will be possible by 2018 with the early GAIA data releases.

Our approach to this program is two-fold. In the first stage we will obtain a series of three to four visible light spectra of each candidate spectroscopic binary in Tobin et al. (2013). High-resolution ($\sim$40,000) visible light spectroscopy is adequate for identifying binaries through RV variability, and the multiplexing available with the Hectochelle instrument at the 6.5-m MMT telescope (Szentgyorgyi et al. 2011) greatly increases observing efficiency. About a third to a half of the systems we expect will be identifiable as double-lined binaries on the basis of the Hectochelle data alone. Following Wilson (1941), it is possible to determine the mass ratio and center of mass velocity of a spectroscopic binary on the basis of at least 3 radial velocity measurements of both the primary and secondary (e.g., Mace et al. 2012).

For other systems confirmed with the Hectochelle+MMT data as spectroscopic binaries, but single-lined, we will in the second stage of this project apply to use the IGRINS high-resolution infrared spectrograph at Lowell Observatory's 4.3-m Discovery Channel Telescope (DCT). IGRINS is currently scheduled on the DCT for three 6-month visits between fall 2016 and late 2018; the first visit in winter 2016–2017 was highly successful. Infrared observations make it possible to measure the radial velocity of the secondary star in small mass ratio binaries (e.g., Prato et al. 2002). This is because flux scales as a steeper function of mass in visible light than in the near-IR (Figure 3). PI Prato is a member of the IGRINS science team and is on the staff at Lowell and has already successfully obtained a large allocation of IGRINS nights in October–November, 2016. Similarly generous allocations are anticipated in the next IGRINS visits.

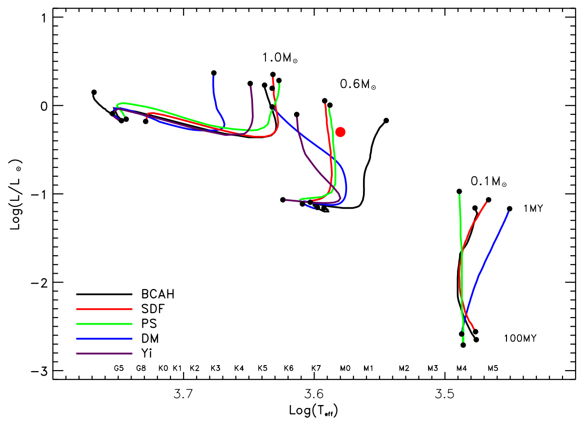

Figure 1: Simon (2008)'s illustration of scatter in low-mass evolutionary tracks (Baraffe et al. 1998; Siess et al. 2000; Palla & Stahler 1999; D'Antona & Mazzitelli 1994; Yi et al. 2003). The red dot shows typical values of L and T_{eff} for a young M0.

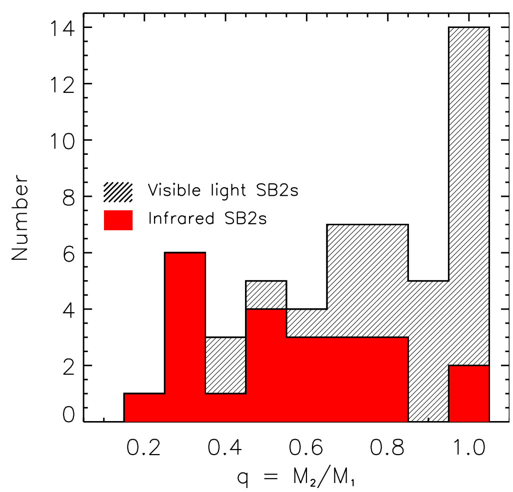

Figure 2: Mass ratio distribution for all known young double-lined spectroscopic binaries.

Baraffe et al. 2015, A&A, in press
Bate 2012, MNRAS, 419, 3115
Kounkel et al. 2016, ApJ, 821,8
Mace et al. 2012, AJ, 144, 55
Prato et al. 2002, ApJ, 569, 863
Simon 2008, The Power of Optical/IR Interferometry, 227
Szentgyorgyi et al. 2011, PASP, 123, 1188
Tobin et al. 2009, ApJ, 697, 1103
Tobin et al. 2013, ApJ, 773, 81
Weinberger et al. 2013, ApJ, 762, 118
Wilson 1941, ApJ, 93, 29

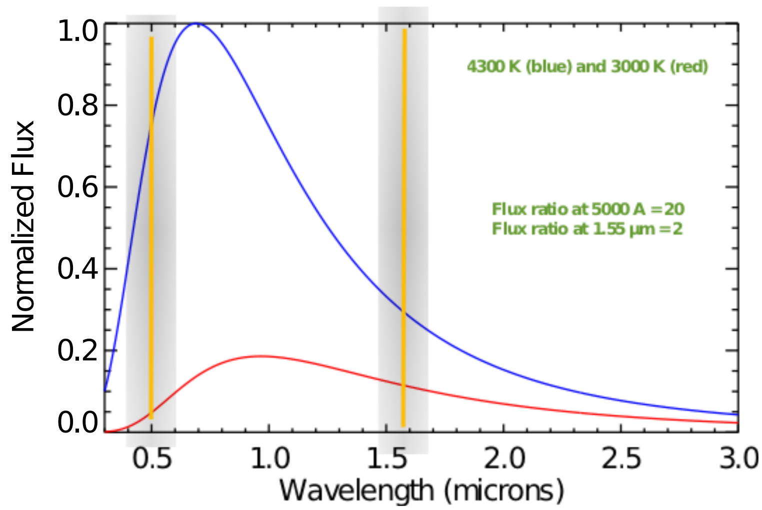

Figure 3: Black body curves for 4300 K (blue, late K) and 3000 K (red, late M) stars. Vertical gold lines indicate the V and H bands.

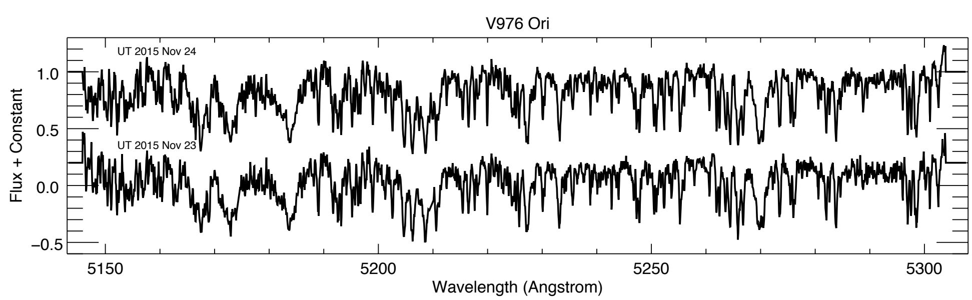

Figure 4: Reduced data for our target V976 Ori on UT 2015 Nov 23 and 24.

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 Hectochelle multi-fiber instrument is capable of recording up to 240 spectra simultaneously at R=38,000 over a 1 degree field of view (Szentgyorgyi et al. 2011). The spectral range is 150Å in width. By focussing on the order containing the MgI lines around 5225 Å, precision of 0.5 km/s is attainable with a signal-to-noise ratio (S/N) of $\sim$20. For targets of magnitude V$<$16 mag, S/N$=$20 or better can be accomplished in $\lesssim$4 hours, divided into four or five 45-minute integrations. The remarkable efficiency of Hectochelle will allow all 120 targets in the ONC candidate sample to be observed simultaneously at the desired S/N in a 3$-$4 hour period.

Our observing strategy is to obtain 3–4 sets of spectra sampled irregularly in time in order to identify spectroscopic binaries over a wide range of orbital periods. We received one set of spectra from November, 2015; the night of UT 2015 Nov 24 yielded good data. On UT 2015 Nov 23 the signal to noise on the fainter objects was insufficient. We now requesting 2 additional epochs of spectra on our targets, separated by 3 or 4 days, in Oct–Dec 2017; we may request one final epoch in February, 2018. Given the total integration time required for one set of spectra, $\sim$4 hours, the current request can be accomplished with the equivalent of 1 night of observing time, a modest investment, in 2017B.

Team member Szentgyorgyi is the Hectochelle PI, team member Torres is an expert in stellar radial velocity measurements for spectroscopic binaries, and team member Nofi is doing her PhD thesis on precision radial velocity measurements of young stars. Our team possesses the expertise and software resources for the expeditious reduction and analysis of the data. PI Prato was awarded a 3 year NSF grant in late 2015 to support this research.

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**)*

Note to TAC: this is a resubmission of our successful 2015B proposal which was awarded one night. Observations were carried out on UT 2015 Nov 23 and 24; the data have been reduced and partially analyzed (e.g., Figure 4). The data from Nov 23 are not of very high quality for the fainter sources. We were awarded a night of DDT time on March 3, 2017, but Hectochelle's fiber positioner failed that morning. We are requesting two more epochs of observations in order to obtain the requisite three epochs of high quality data on each of the targets in our field.

We are currently requesting 1 night in semester 2017B. In future semesters we may request additional time in order to fully characterize the orbits of confirmed binaries but that would comprise a separate effort.

Observing time with the IGRINS high-resolution infrared spectrograph at the 4.3-m DCT telescope at Lowell Observatory will complement the program proposed here by capitalizing on low-mass ratio spectroscopic binaries identified by Hectochelle to determine their mass ratios in the infrared. PI Prato is a member of the IGRINS science team and the IGRINS+DCT instrument scientist and has already been successful in obtaining large time allocations with IGRINS on the DCT.

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**)*

PI Prato has never before used Steward Observatory facilities but co-I Szentgyorgyi is the Hectochelle PI.

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**)*

In September, 2015, PI Prato was awarded an NSF grant in support of the data processing, analysis, and publication of the observations proposed here.