The *CASTOFFS* Survey: High Resolution Optical Spectroscopy of Bright Targets

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Abstract. The census of young stars near the Sun is incomplete, particularly at low-masses. Many constituents of the known sample are members of nearby, young moving groups (NYMGs); loose associations of coeval stars with common Galactic kinematics. By mining astrometric and photometric catalogs, new candidates of the young, low-mass star population can be found via their association with NYMGs. We have therefore developed the **C**ool **A**strometrically **S**elected **T**argets **O**ptimal **F**or **F**ollow-up **S**pectroscopy (*CASTOFFS*) survey to identify and characterize previously unrecognized young, low-mass stars. We combine astrometry, photometry, and activity to identify candidates and use dedicated spectroscopic follow-up to verify their youth and group kinematics. We are now 2 years into *CASTOFFS* and present preliminary results from spectroscopic follow-up of 62 targets with $V \leq 14$. Our results reveal many high probability members of NYMGs, young field stars, and new wide, visual, and spectroscopic binaries.

1. Introduction

Young stars, with ages ∼10-100 Myr, populate the first ∼100 pc beyond the Sun as members of loosely bound, co-evolving associations where members have common Galactic motion (Zuckerman & Song 2004; Torres et al. 2008). These associations are collectively known as nearby, young moving groups (NYMGs, e.g. the β Pictoris moving group). The youth and proximity of NYMG members have repeatedly led to breakthrough discoveries in the formation and evolution of planetary systems. These include the first resolved images of debris disks and giant extrasolar planets (Smith & Terrile 1984; Marois et al. 2008; Lagrange et al. 2009). The lists of proposed NYMG members in the review of Torres et al. (2008) revealed that most known members have spectral types F, G, and K. However, studies of other stellar populations in the Milky Way reveal that the majority of stars (∼70%) are low-mass M dwarfs (Chabrier 2005). Thus, NYMGs have a deficit of M dwarfs, which are otherwise ubiquitous in the universe. For example, the 50 pc NYMG member sample in Torres et al. (2008) is comprised of only ∼30% M dwarfs. Nearly 200 additional low-mass members remain to be found to raise their numbers up to the expected M dwarf population. The incompleteness of M dwarfs in NYMGs can be attributed to their low-luminosities, wide sky distribution, and difficulties in age dating.

Despite small number statistics, nearby, young M dwarfs are a boon for the study of star formation and evolution; in particular, the study of youth indicators over critical periods of evolution, the identification of benchmark systems for the calibration of models, and the direct detection of giant planet and brown dwarf companions via high contrast imaging. Thus, the search for young M dwarfs has accelerated in recent years. Our early efforts to identify low-mass NYMG members focused on the β Pictoris and AB Doradus moving groups and are detailed in Lépine & Simon (2009) and Schlieder et al. (2010, 2012a,c). Other researchers have used new data from the Galex and WISE satellites to identify low-mass candidates via UV and mid-IR excesses (Shkolnik et al. 2011; Rodriguez et al. 2011; Schneider et al. 2012; Rodriguez et al. 2013). Novel selection methods using Bayesian techniques have also been developed and used to identify dozens of high probability low-mass and substellar moving group candidates (Malo et al. 2013, 2014; Gagné et al. 2014). Data from dedicated spectroscopy and parallax programs have revealed additional NYMG candidates and confirmed many of those previously proposed (Shkolnik et al. 2012; Riedel et al. 2014; Kraus et al. 2014).

However, M dwarf populations in NYMGs remain incomplete and revised group mass functions are still inconsistent with the accepted initial mass function (e.g. Shkolnik et al. 2012; Kraus et al. 2014). To address this incompleteness and continue the identification of new low-mass moving group members, we have expanded our previous work and applied our selection criteria to a deep, all-sky proper motion catalog to identify candidates in more

NYMGs. We call this new program the **C**ool **A**strometrically **S**elected **T**argets **O**ptimal **F**or **F**ollow-up **S**pectroscopy (*CASTOFFS*) survey. In this proceeding, we present preliminary results from the *CASTOFFS* spectroscopic follow-up campaign.

2. Candidate Selection

CASTOFFS candidates are selected using a multi-step algorithm that hinges on proper motion and photometry (Lépine & Simon 2009; Schlieder et al. 2010). The steps in the process are described in detail in Schlieder et al. (2012a); we provide a summary here. First, the bulk Galactic motion of an NYMG is projected onto the plane of the sky at the location of each star in a proper motion catalog. Any stars having a proper motion vector within 10° of the projected group motion are retained. Second, a color-magnitude-diagram (CMD) is constructed using a kinematic distance that is calculated assuming each of these stars is a member of the NYMG. Any star that has photometry consistent with this assumed distance will match the NYMG locus in the CMD. Stars falling above or below the group locus have their true distances under or overestimated when assuming group membership and are removed from the sample. Third, a photometric color cut is used to select only the remaining low-mass stars. Candidates selected in this way are then vetted for coronal and chromospheric activity, signatures of youth in low-mass stars, using the *ROSAT* X-ray and *GALEX* UV catalogs following the methods described in Shkolnik et al. (2009) and Shkolnik et al. (2011) (see Schlieder et al. 2012a). The final list of active, NYMG candidates is targeted for follow-up spectroscopy.

The *CASTOFFS* input search catalog is the SUPERBLINK proper motion database (Lépine & Shara 2005; Lépine & Gaidos 2011), an all-sky catalog of positions, proper motions, and photometry ($VJHK$) for more than 2 million stars with μ>40 mas yr^{-1} and $V\leq$19. These limits are ideal to identify nearby, faint M dwarfs. Our search of SUPERBLINK using the selection methods described above resulted in nearly 400 candidates with activity-estimated ages $\leq$300 Myr and masses <0.7 $M_{\odot}$. These candidates are potential members of the four closest and youngest NYMGs; the TW Hydrae association ($\sim$10 Myr), the β Pictoris moving group ($\sim$20 Myr), the Tucana/Horologium association ($\sim$40 Myr), and the AB Doradus moving group ($\sim$100 Myr) (Weinberger et al. 2013; Binks & Jeffries 2014; Kraus et al. 2014; Barenfeld et al. 2013, and references therein). For the last two years, we have pursued high-resolution spectroscopic follow-up of these targets and have acquired hundreds of spectra at optical and near infra-red wavelengths. Early results from the survey include two young, low-mass multiple systems that are new benchmarks in the study of debris disks and the calibration of stellar evolution models (Schlieder et al. 2014; Deacon et al. 2013).

3. Observations and Data Reduction

We present here observations of 62 targets in the *CASTOFFS* bright ($V \leq 14$) candidate subsample that were observed using FEROS on 2011 December 4 and 5 UT and 2012 October 1, 2, 3, 7, 8, and 12 UT. FEROS, a high-resolution, fiber-fed, optical Échelle spectrograph is mounted to the Cassegrain focus of the ESO/MPG 2.2m telescope at the La Silla observatory. The instrument covers $\sim$3500 to 9200 Å over 39 orders at a spectral resolution of R$\approx$48000 (Kaufer & Pasquini 1998). FEROS contains two 2.0$''$ optical fibers separated by 2.9$'$ on sky. We observed in '*object + sky*' mode with one fiber on the science target and the other on sky. Data reduction was performed using the FEROS Data Reduction System (DRS) implemented within the ESO-MIDAS software package. The DRS performs flat-fielding, background subtraction, bad pixel removal, order extraction, and wavelength calibration from ThAr lamp lines. The DRS then computes barycentric velocity corrections[1] and rebins the individual orders to the same wavelength scale to merge them and produce a continuous spectrum.

Our targets were observed with total integration times from 60s to 3600s broken into integrations no longer than 600s. After median combining the reduced spectra of targets with multiple individual integrations, these integration times produced signal-to-noise ratios ranging from ∼20 - 100. We also observed late-type radial velocity (RV) templates drawn from Prato et al. (2002) throughout the December 2011 and October 2012 observing runs for later use during cross-correlation analyses. Each night of FEROS observations also included observations of at least one RV standard drawn from the lists of Chubak et al. (2012) or Nidever et al. (2002) for internal calibration checks. These RV templates and standards were reduced in the same way as the science targets.

4. Analyses and Results

To verify the NYMG membership of our candidates we investigate multiple spectroscopic youth indicators and measure their RVs to compare their kinematics to bulk NYMG kinematic distributions.

4.1 Youth Indicators

We focus on spectroscopic indications of chromospheric activity, primarily emission from the hydrogen Balmer series, and lithium absorption at 6707.8 Å. Both hydrogen emission and Li absorption are strong indicators of youth in early to mid M dwarfs with ages ∼10 - 100 Myr (Zuckerman & Song 2004; Torres et al. 2008). We first perform a visual inspection of spectral regions of interest containing these features and then measure equivalent widths (EW) following the methods detailed in Sembach & Savage (1992).

More than 50% of our 62 targets exhibit at least Hα in emission and many of those exhibit multiple lines in the Balmer series in emission; all the way down to Hϵ ($\lambda = 3970$ Å). The strongest chromospheric emitters also exhibit reversed emission cores in the Na D doublet around 5900 Å and the Ca II infrared triplet between ∼8490 and 8670 Å. Some targets also exhibit He I emission at 5875.6 Å. Seven targets have Li in absorption in addition to chromospheric emission. These are shown in Figure .1 compared to a late-K dwarf spectral template. Each spectrum has been normalized to the continuum, shifted by its RV, and offset by an arbitrary constant in flux for clarity. The field age RV template exhibits no Li absorption and the ∼K5 - M2 NYMG candidates exhibit absorption with EWs between ∼40 and 200 mÅ.

[1] Müller et al. (2013) show that the barycentric correction computed by the FEROS-DRS is only accurate to ∼100 m s^{-1} because it does not take into account coordinate precession. This small systematic error is not significant for our analyses which achieve a RV precision of ∼1000 m s^{-1}.

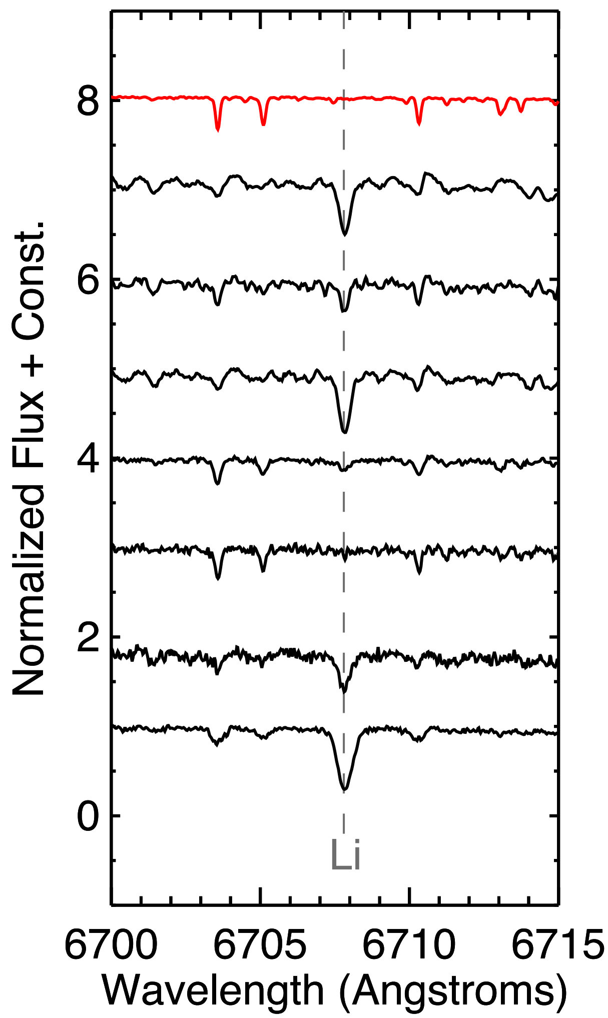

Figure .1: FEROS Order 30 spectra of candidate NYMG members (black) and a main sequence, late-K dwarf (red) centered on the Li line at 6707.8 Å. With spectral types K5 to M2, the detection of Li is a strong indicator of youth in these stars. Each of the candidate members also exhibits strong chromospheric emission and has proper motions and a measured RV consistent with group membership.

4.2 Radial Velocities

Target RVs are measured via cross-correlation (CC) against a suite of late-type RV templates. We use a custom IDL routine capable of two-dimensional CCs for the measurement of component RVs in spectroscopic binaries (see Bender & Simon 2008). To prepare our targets for the CC analysis, we first trim regions-of-interest (ROIs) from our extracted, median combined spectra that are relatively free of telluric absorption in 6 different spectral orders. These ROIs are then continuum normalized and cross-correlated with identical regions in our suite of K5 - M5 templates. The CC analysis provides a RV and uncertainty from a

Gaussian fit to the peak of the CC function and an estimate of target spectral type (from the template that maximizes the CC power). Our FEROS RVs have typical uncertainties of ∼1 km s^{-1} which comes mostly from a systematic uncertainty introduced by the use of observed templates. We also measure target rotational velocities ($v\sin i$) by rotationally broadening our templates in increments of 2 km s^{-1} and performing the RV analysis again to search for the template $v\sin i$ that maximizes the power in the CC function. In some cases, the CC analysis produced a dual-peaked correlation function, which is indication of an unresolved binary. These stars were subject to a full, two-dimensional CC analysis to estimate component spectral types and measure their RVs, $v\sin i$'s and flux ratios (see Discussion).

To evaluate consistent NYMG kinematics, the measured RVs are compared to a RV predicted during target selection that assumes group membership. Targets with RVs that match the NYMG prediction within 5 km s^{-1} are retained further as candidates. 39 of our 62 spectroscopy targets met this RV criterion and each exhibited spectroscopic youth indicators consistent with NYMG ages. Henceforth, we refer to these candidates as RV match candidates (RMCs).

5. Discussion

5.1 Galactic Kinematics

The members of NYMGs are defined by common Galactic kinematics and common age. We use positions and proper motions from the SUPERBLINK database, our measured RVs, and estimated distances to calculate the UVW Galactic space velocities of each RMC. We follow the procedures outlined in Johnson & Soderblom (1987) to compute the Galactic velocities and their uncertainties. Each of our RMCs have UVW velocities consistent within 2σ of their respective group. Figure .2 shows an example of our *CASTOFFS* AB Doradus moving group RMCs compared to bona-fide members from Malo et al. (2013). Trigonometric distances do not exist for the majority of the *CASTOFFS* sample and we rely here on photometric and kinematic estimates. Parallaxes from the first *Gaia* data release will place better constraints on the stars' kinematics.

As a further check of membership, we also used the online tool BANYAN II[2] (Malo et al. 2013; Gagné et al. 2014) to calculate RMC membership probabilities. BANYAN II is a naive Bayesian classifier that uses available kinematic data and non-uniform priors in NYMG kinematics to assign membership probabilities to a given star in eight different populations; 7 NYMGs and the Galactic field. The tool also allows the user to select from two different age distributions for the Galactic field: young (<1 Gyr) and old (>1 Gyr). Since our targets all exhibit strong activity and some exhibit Li, we always chose the young field distribution. BANYAN II returns NYMG membership probabilities for our RMCs ranging from negligible to >99%. While the UVW velocities of the stars with negligible membership probability are consistent with their candidate NYMGs, their XYZ Galactic positions typically lie significantly outside the bounds used as priors in BANYAN II. These candidates may represent new NYMG members in previously unexplored parameter space or are isolated young field stars with kinematics comparable to true moving group members by chance.

[2]http://www.astro.umontreal.ca/ gagne/banyanII.php

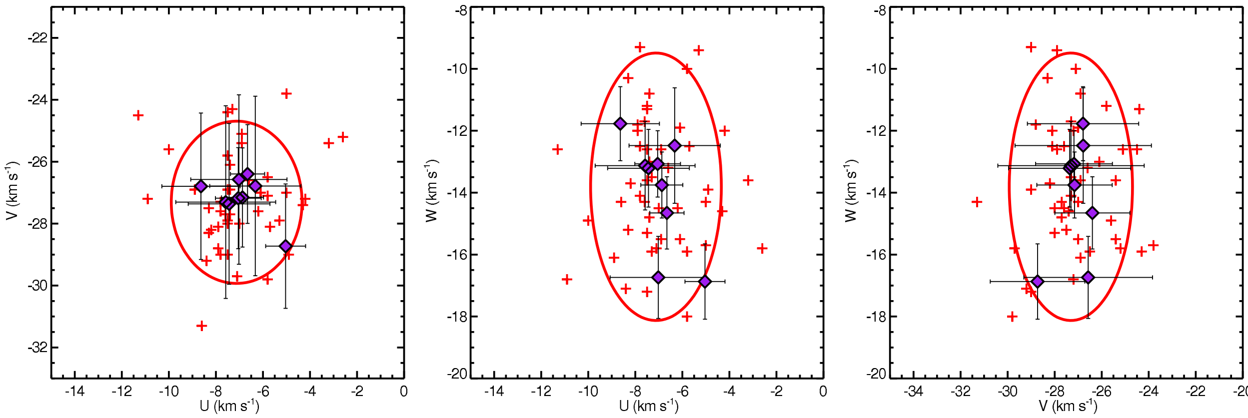

Figure .2: UVW space velocity projections for known members of the AB Doradus moving group with 2σ uncertainty ellipses (red, Malo et al. 2013) compared to RMCs from *CASTOFFS* (purple).

5.2 Multiple Systems

Multiple systems are critical for understanding star formation and evolution and calibration of widely used stellar evolution models (e.g. Bonnefoy et al. 2009) The *CASTOFFS* survey has already produced one young, benchmark binary (Schlieder et al. 2014) and the RMC sample presented here contains 5 additional visual binaries. Several of these systems have sub-arcsecond projected separations and may be amenable to orbital monitoring for mass measurements (Figure .3a). The RMC sample also contains several wide binaries, two of which are hierarchical multiples and may in the future provide self contained systems for calibrating models over a wide range of M dwarf masses at the same age. Our CC analyses also revealed two spectroscopic binaries in the RMC sample for which we were able to measure parameters for each component. An example of one of these systems is shown in Figures .3b,c compared to a single star with approximately the same age and spectral type. Double features are obvious, indicating a system caught at a relatively wide velocity separation and likely having a short period. Further monitoring of these systems will provide systemic velocities for verification of NYMG kinematics and orbital parameters. The multiple systems in the RMC sample are not surprising, given that part of our selection procedure uses CMDs and field age unresolved binaries may masquerade as younger stars. Additionally, field SBs may be spun up via tidal interaction to become anomalously active. However, available data indicates these systems are strong NYMG candidates, not field contaminants, and they are a substantial increase to the pool of candidate low-mass multiples in NYMGs.

6. Conclusion

We introduce the *CASTOFFS* survey and present preliminary results from our all-sky spectroscopic follow-up campaign. Our FEROS spectroscopy of a subsample of bright NYMG candidates reveals nearly 40 stars having available kinematics and spectroscopic age indicators compatible with group membership. Several of these stars are in multiple systems and some provide the opportunity to measure orbital parameters, derive fundamental prop-

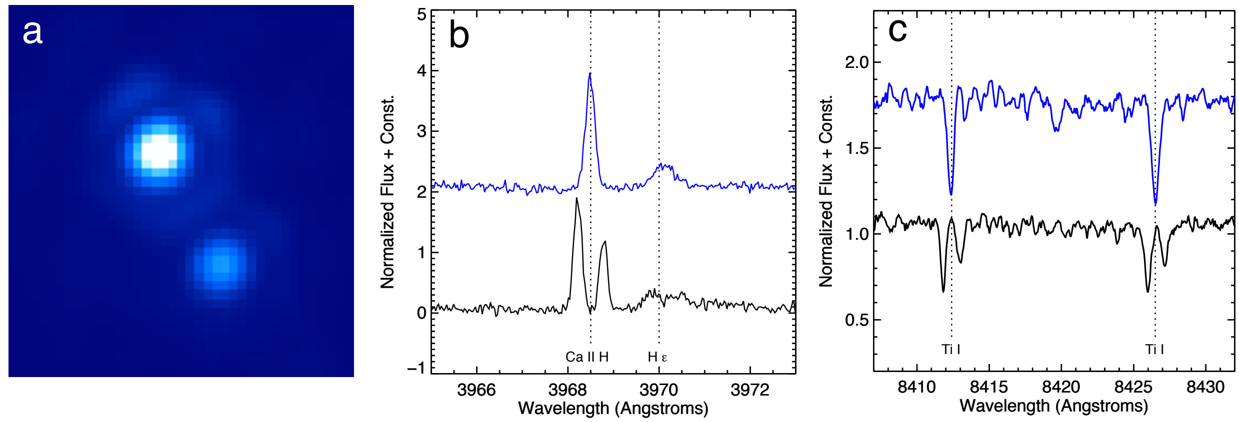

Figure .3: a) Keck/NIRC2 K_s-band adaptive optics image of a candidate β Pictoris moving group member revealing a close, lower-mass companion. The measured angular separation translates to a physical separation of ∼10 AU at the estimated distance of the star. b,c) FEROS spectral regions of a spectroscopic binary (SB) candidate of the β Pictoris moving group (black) compared to a single candidate with similar spectral type (blue). Emission and absorption features in the SB spectrum are split into individual components separated by >40 km s^{-1}. Continued monitoring of these systems can yield orbital parameters and provide new benchmarks for the calibration of models.

erties (i.e. mass), and calibrate stellar evolution models. The *CASTOFFS* survey is making significant contributions to the incomplete sample of young, low-mass stars in the solar neighborhood and these results give an indication of what can be expected from the full survey. A larger, more detailed study of >100 FEROS spectra of *CASTOFFS* candidates will be described in a forthcoming publication (Schlieder et al. 2014 in prep.).

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One of the many breakfast clubs at CS18: Kelle Cruz, Jackie Faherty, Joe Fillipazzo, Adric Riedel